STAT

The Testing of Materials and Manufactured Goods With X-Rays

By: Professor A. K. Trapeznikov

Kontrol' Materialov and Izdeliy Rentgenovymi Luchami, Moscow, 1951

(a 74-page book)

STAT

Professor A. K. Trapeznikov

Doctor of Physio-Mathematical Sciences

THE TESTING OF MATERIALS AND MANUFACTURED GOODS WITH X-RAYS

The State Scientific and Technical Press

for Machine-Building Literature

Moscow 1951

INTRODUCTION

Methods of testing materials and manufactured goods can be divided into two groups: tests which involve the destruction of samples of the materials or manufactured goods, and tests which do not require destruction of the object.

In the first category, materials or goods to be tested are subjected to tearing, breaking, shock, crushing, pressure, vibration, etc, on special machines. The load which causes breakdown or the length of time a certain load must be applied for breakdown is determined. These loads and times must correspond with previously-determined norms. Besides this, specially prepared sections of the materials are examined microscopically for the determination of their internal structure (microstructure), which must correspond to certain norms. Tests which involve the destruction of the object cannot be carried out on all series-produced objects.

The second group of tests, which leaves the materials or goods intact, can be used for checking the entire output.

At the present time, the following methods of testing which do not involve destruction are in wide use: magnetic, X-ray, Gamma-ray, ultra-sonic and luminescent. Each of these methods has its advantages and shortcomings, certain limits of application and intrinsic sensitivity for detecting hidden defects.

However, not all of the indicated methods can or should be applied to one and the same object. Depending on the type of material, the sort of manufactured item, and characteristics of the defects which are to be found, one or another of the methods is used.

In some instances it is advantageous and possible to apply still other methods of nondestructive testing.

The method of X-ray testing has a relatively great historical background. Its first application may be dated from 1895, i.e., the year in which Roentgen published his paper on "X"-rays. In the US, France, and England they are known by this name. In the USSR and Germany they are better known as Roentgen rays. Soon after their discovery these rays were used in medicine for the study of internal disorders in the human body; this was called medical X-ray diagnosis. X-rays could not be used at first for the study of parts, particularly metal parts, because of the low power of X-ray equipment and tubes, whose design was just in its initial stages of development. In about 1915 there appeared a paper in the technical literature about the use of X-rays for the examination of metallic objects. In the twenties, special laboratories were equipped for the radioscopy of items produced by the metal industries (castings, welds, riveted joints, etc).

During the development of the aircraft industry, where welding and light-metal castings are widely used, this method of checking came into particularly general application. It is also notable that even before World War II X-rays were in wide use in the aircraft industry, and the methods of the USSR were already in advance of those of the US.

If one of our methods gives reliable results and it is considered worthwhile to apply it, the Soviet government provides the necessary materials for its wide introduction. A number of valuable suggestions on methods of radioscopy, application of X-ray equipment, and design of essential auxiliary apparatus were made by

workers in plant X-ray laboratories. At the present time, this checking method is widely used in a variety of industries; in the near future it will be introduced into those branches of industry where it may facilitate higher quality production. All checking methods which do not require destruction of the object not only expose production rejects, but what is particularly essential, disclose the defects in materials and determine the reasons for one or another kind of defect, thus leading to the change and improvement of production technology. In plants where new production methods are being developed, one or another of its aspects is usually checked 100 percent. The identification of rejects, and the presence of defects in the goods leads to changes in production and improvement of the goods. Testing of the same parts after changes in their production technology allows evaluation of the worth of the changes. If a flaw which was present in a part is no longer found after the technological change, the check may be cut down, i.e., applied only to a certain percentage of the daily production. The nondestructive testing of materials also increases the skills of the shop workers making the item. Many examples can be cited which illustrate the decrease of rejects, for example, of non-fused welded joints, after the institution of X-ray control at a number of plants. This is explained by the fact that welders, who were given the opportunity to see X-ray pictures of welding failures, were able to improve their techniques. Such improvements in production technology can take place when there is the close communication and cooperation between the X-ray laboratories and production shops.

It is difficult to name all the branches of industry where X-ray control methods are being or can be applied. This testing method makes it easy to determine the quality of rubber, coal,

plastics, wood; it also allows the distinction of a copy from an original picture, the examination of tissues, porcelain insulators, the quality of castings and welds, the internal contours of hidden mechanisms, etc.

Subsequently, we will try to acquaint the reader with the essentials of this method of control, how it allows defects to be discovered in parts, and its achievements in this direction at the present time.

THE GENERATION OF X-RAYS

It is essential to have the proper apparatus for producing X-rays. Basically such equipment includes a high-voltage generator (usually a transformer), a table or supporting stand and X-ray tube. The X-rays emanate from the tube and are directed at the tested object. A diagram of such a tube is presented in Figure 1.

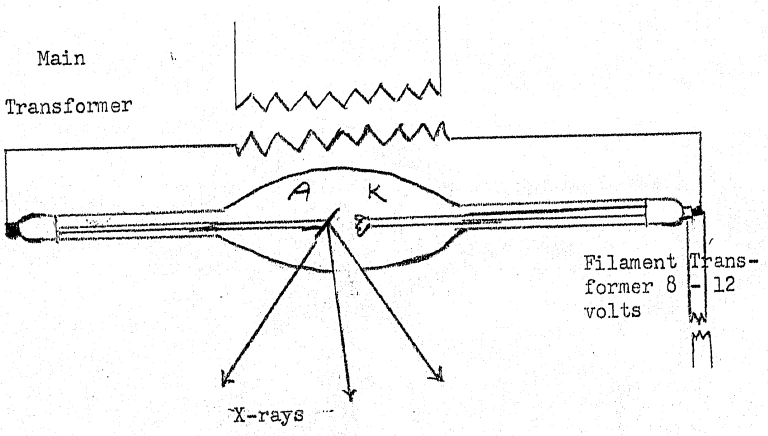

Figure 1. General Working Diagram of an X-ray Tube: A -- Anode; K -- Cathode; T_r -- Main Transformer; $T_{r.f.}$ -- Filament Transformer

Essentially, it consists of a glass vessel from which the air has been exhausted to within a few millionths of 1 millimeter Hg. The vessel may be in the form of a cylinder, or as shown in Figure 1, ballooned-out in the middle. Metal electrode poles are fused into both ends of the tube. One of them, usually plated with tungsten is called the anode. The other electrode, the cathode, is a spiral made of thin tungsten wire with a diameter of about 0.2 millimeters, anchored in the base of the metal cap. The ends of the spiral pass through the sealed base of the tube and are attached to the secondary winding of a small transformer which delivers a potential of 8 - 12 volts. The primary winding of the transformer supplies 120 - 220 volts. If the secondary winding of this type of transformer (called a filament transformer) is connected to the spiral, it glows and gives off electrons (the so-called thermo-electronic effect). The electrons are particles carrying a negative electric charge which up to this time is the smallest known (the so-called elementary unit of electric charge). If both electrodes are now connected to the high voltage source (generator), one to the positive and the other to the negative end of the secondary winding, a strong electric field will be developed between the tube electrodes. Electrons emitted from the electrode connected to the negative end of the secondary winding, i.e., the cathode, are accelerated to some extent in this field toward the positively charged anode, because of their negative charge. They fly to the anode and reach its surface (the so-called mirror of the anode) with a velocity which depends on the voltage across the poles (electrodes) of the tube.

This stream of electrons produces a certain current in the tube as long as its electrodes are under high voltage. The flat mirror-surface of the anode, at which the electron stream is directed,

is called the focus of the anode or the focus of the tube. Each electron in the stream may be compared to a bullet directed toward a target. Such a bullet of mass m and with a velocity v has a kinetic energy of $mv^2/2$ on reaching the target. On hitting the target, the bullet loses its velocity and therefore its energy of motion. According to the law of conservation of energy the latter is not lost but rather is transformed into a different form of energy, i.e., at its expense some work is done, such as damaging the area which the bullet hit, with the latters deformation; often the energy of motion is converted to warmth; the bullet is heated. If the bullet strikes armor which it cannot penetrate, it is flattened, with the concurrent production of heat. Analogous phenomena are observed when electrons strike the mirror anode of the tube. They lose their velocity, penetrating the anode for a very short distance, as they are deaccelerated and captured by the atoms of the mirror material. The energy of motion which they lose in this process passes partly into heat, which heats up the anode, and partly into radiant energy, the energy of the X-rays. It is essential to note that only a small portion of the energy of the motion of the electrons passes into the latter (a maximum of a few percent). Most of it is transformed into heat; because of this, if an X-ray tube is used continuously its anode may become very hot, even to the extent of a local melting of the mirror. For this reason, a metal with a high melting point is chosen for the anode mirror material, for example tungsten, with a melting point of 3,300 degrees; besides this, the anode is cooled with running water or oil, using a pump connected through the supporting base of the anode. Some designs make use of finned radiators projecting from the anode base of the tube, which dissipate the heat to the surrounding air. Each type

of tube is designed for a certain maximum load, indicated on the rating plate of the tube. This load should not be exceeded in practice.

The greater the energy of the electrons, i.e., their quantity and velocity, the greater the energy of the X-rays that they produce.

The quantity of electrons freed at the cathode when it is heated determines the strength of the anodal current in the tube and depends on the temperature of the spiral cathode. The higher the temperature, the greater the quantity of electrons, and the stronger the anodal current and intensity of the X-rays. This intensity is proportional to the strength of the anodal current in the tube. The velocity depends on the voltage applied to the ends of the tube. The greater it is, the higher the velocity of the electrons, and consequently, the more energy they have, producing stronger X-radiation. The power (energy per second) radiated by the tube is proportional to the square of the voltage. Thus if the voltage is doubled with the same strength of current in the tube, the power of the X-rays is increased 4 times; when the voltage is increased 3 times the power increases 9 times, etc.

In this way the radiated power can be regulated by changing both the current strength and voltage. However, one must note that by changing the current in the tube only the quantity or power of radiation is changed. With changes in voltage, besides a change in power, there is a concurrent change in the quality of the radiation. With an increase in voltage, the X-rays produced pass through substances more easily and penetrate to a greater depth in a particular material. They become, as is commonly said, harder. In summary,

one can change not only the quantity of radiation emitted from the tube (by changing only the current strength), but also its quality (by changing the voltage). The high voltage, as has already been indicated, is produced by the main transformer, which converts the relatively low voltage of the lines that it draws from into voltages of tens and hundreds of thousands of volts. The transformer is composed of two wire windings, the primary and secondary, wound on a common iron core (magnetic circuit). Current of low voltage is fed through the primary. Its intensity is regulated at the control table (stand) which is connected to the electric lines (127, 220, 380 volts). A magnetic current is generated in the core by the passage of the low-voltage alternating current through the primary winding of the transformer. This produces (induces) electromotive force in each turn of the secondary winding. As a result of the summation of all the turns, a powerful electric force (voltage) appears across the ends of the secondary. The greater the number of turns in the secondary, the greater the voltage across its ends. If the number of turns in the primary is equal to n_1 and that in the secondary n_2, and the voltages across these windings is U_1 and U_2, the following relationship is obtained:

$$U_1 : U_2 = n_1 : n_2 \qquad (1)$$

According to the law of conservation of energy, it is impossible to obtain more power from the secondary winding than is in the primary. The power of the electrical energy is measured by the product of the generated voltage and the current. Because of this, the following relationship must hold:

$$i_1 U_1 = i_2 U_2 \qquad (2)$$

where i_1 is the current in the primary winding and i_2 is the current in the secondary winding.

From equation (2) we obtain:

$$U_1 : U_2 = i_2 : i_1 \qquad (3)$$

Substituting the current strengths in equation (1), instead of $U_1 : U_2$, in the basis of (3), we obtain:

$$i_2 : i_1 = n_1 : n_2 \qquad (4)$$

i.e., the strength of the current in the two windings will be inversely proportional to the number of windings. To put it another way, there is a low voltage and high current in the primary of the transformer, and in the secondary, a high voltage and low current. This means that if a high voltage from a transformer is applied to the poles of the X-ray tube, the current in the tube will be small. Usually the current strength in primaries of X-ray transformers is given in amperes or tens of amperes; in X-ray tubes in milliamperes or tens of milliamperes, i.e., thousandths or hundredths of an ampere. The ends of the secondary winding of the transformer, carried out to insulators, are connected to the poles of the tube by special high-voltage lines. Both windings of the transformer must be well insulated from each other. Besides the dry insulation composed of insulating paper, special separators, etc, the transformer tank may be filled with transformer oil, which also serves the purpose of removing heat produced by the current flow. Figure 2 is a schematic representation of the main features of a transformer.

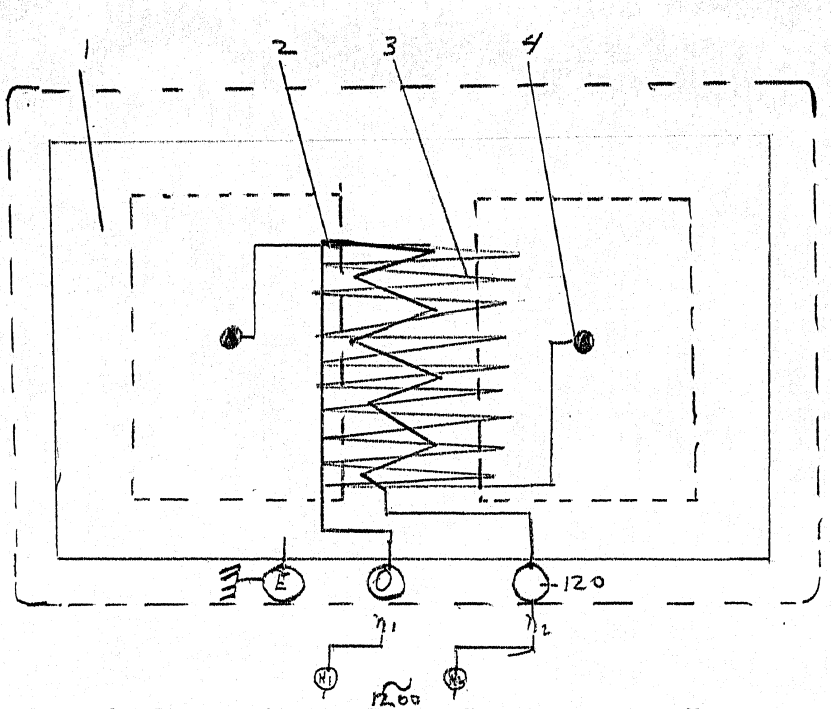

Figure 2. Diagram of a High-Voltage Transformer: 1 -- Magnetic Circuit Core; 2 -- Primary Winding; 3 -- Secondary Winding; 4 -- High-Voltage Outlets (Poles); L_1 and L_2 -- Leads Carrying Low Voltages from Lines; E -- Ground

As is shown below, the quantity and quality of X-rays plays a very important role in the success of locating hidden flaws in materials. Depending on the material and its thickness, it is necessary to establish suitable working values. In view of the great variety of objects which are X-rayed, it is essential to make provisions for changing the working values (particularly the tube voltage), which influence the radiation quality. It is technically impossible and inefficient to build a transformer which gives any voltage from the lowest to the highest possible.

Depending on the requirements of the X-ray apparatus, the transformer is designed for a certain range of voltages. At the present time, basic attention should be given to the types of equipment listed in Table 1.

TABLE 1

TYPES OF X-RAY EQUIPMENT AND THEIR USE

Limits of Working Voltage in Kv* [1]	Use of Apparatus [2]
5 - 15	In medicine for superficial cutaneous therapy. Useful for the radioscopy of very thin materials which absorb X-rays with difficulty.
30 - 50	For the radioscopy of pictures and nonmetallic objects; light aluminum or magnesium alloys with a thickness of up to about 6 mm with 30 Kv and about 30 mm with 50 Kv.
60 - 80	In medical wards for diagnosis. 80 Kv can penetrate about 50 mm of aluminum or 6 mm of steel.
110 - 125	For medical diagnosis with stationary equipment. When used for radioscopy of materials, 125 Kv will penetrate aluminum up to about 100 mm thickness, steel of 20 - 30 mm.
200 - 250	In medicine for therapy. Aluminum up to about 350 mm, and steel up to about 70 mm can be tested in industrial X-ray work.
300 - 400	In medicine for therapy. In checking industrial production for penetration of steel 100 - 125 mm thick.

[1] [2]

1000 Penetration of steel up to 200 mm thick.

2000 Allows penetration of steel up to 300 mm thick.

*The voltage produced by the transformer is usually given in kilovolts (1 Kv = 1000 volts)

Examples are presented in Figures 3 and 4 of X-ray equipment of different types. Appropriate X-ray tubes are constructed for the voltages provided by apparatus of various types.

Figure 3. RUP-1 X-ray Apparatus, for 200 Kv, 20 Ma: 1, 2 -- Two Halves of the High-Voltage Transformer; 3 -- Pump for Cooling the Tube with Oil; 4 -- Housing for the X-ray Tube; 5 -- Support; 6 -- Control Table; 7 -- Operating Switch, which Connects the Transformer Primary with the Power Lines via the Operating Table. [Photo]

Figure 4. Transformer with a 1-Million-Volt Tube, supported by a Crane. Under the Tube -- Radiographed Object [Photo]

THE NATURE OF X-RAYS

In order to understand the way in which X-rays can be used to detect hidden defects in materials, it is essential to have a brief acquaintance with their nature and some of their properties.

The immediate excitor of X-rays is free electrons, which reach the anode with great velocity and are stopped on its surface. There are a number of collisions between the electrons and the atoms of the anode material. With each such collision, the energy lost by the electron gives rise to a certain impulse which is dissipated

in surrounding space.

In radio technology it is essential to use an electric force that varies periodically to generate the radio waves, which radiate out into surrounding space from the source. Every change in current, with the simultaneous displacement of electric charge, leads to the formation of an electric field around the moving charge. This field is radiated into surrounding space in all directions, going from point to point with the velocity of light, i.e., 300,000 kilometers per second in a vacuum.

In the case of the movement of the electrons to the anode and their deacceleration, there is also a change in the speed of a moving charge, producing an electric field surrounding the retarded charge. But in contrast to radio waves, the electric field in this case has a somewhat unique character. In radio technology the changes in charging rate take place periodically and continuously, leading to radiation of waves with this type of oscillation. The propagation of periodic oscillations in a plane is easily demonstrated by wave motion, as on the surface of water. If a small piece of wood is thrown on a water surface, circular hills and valleys are seen to spread out from the point of impact of the wood, with constantly increasing radius. The piece of wood at the surface of the water will rock up and down for a certain length of time.

Figure 5 is a schematic representation of the cutting of a water surface by a certain vertical plane (plane of the figure). The x axis represents the propagation direction of an oscillating water particle from point O, where it originated due to the falling piece of wood. We will call this direction the "ray". The y axis gives the displacement of every water particle from the original

surface. In the interval of time (period of oscillation T), during which a single particle of water undergoes a full oscillation (leaves the point of equilibrium O owing to the impact of the piece of wood, sinks, and being joined cohesively with the adjacent particles, rises, passes due to inertia through point O, rises above it, and, again due to cohesion with the other particles, returns to point O), the oscillatory movement traveling from one particle of water to another is propagated a distance λ, called the wave length.

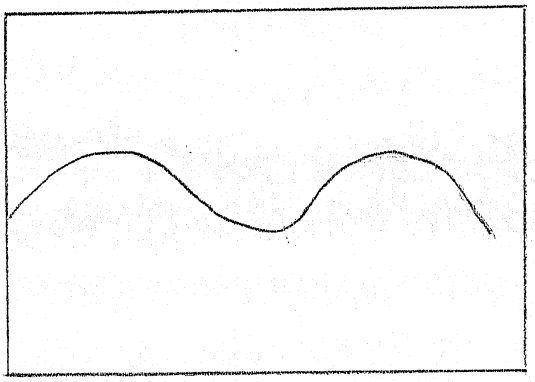

Figure 5. Schematic Representation of a Wave.

λ -- Wavelength

This figure represents the propagation of a wave in one plane only. In the case of a radio wave the analogous oscillation occurs in all planes which pass through the point of origin of the wave. Put in another way, a spherical surface is formed in which all the particles are in the same state of oscillation (in the same phase). In the example with the piece of wood thrown in the water, we have a transformation of its energy into a different form of energy, i.e., into the energy of the oscillations of the medium into which it was thrown. The oscillations gradually die out because of the presence

of cohesive forces between water particles and an absence of a periodic excitation of the oscillations. If, however, such oscillations are produced continuously, as with the base of a tuning fork touching the surface of the water, the phenomena will occur as long as the fork is oscillating, and the distance to which the waves are propagated will be greater. With the dying out of the oscillation of the tuning fork, the oscillation of the water particles will cease. The water surface will once more become smooth.

When electrons are retarded at the anode, such periodicity is not observed. In this case there is a succession of collisions of electrons into the atoms of the anode, each of which produces a certain impulse of an electro-magnetic character. If we compare electro-magnetic oscillation with sound, the generation of a radio wave is somewhat analogous with vibration of a string, giving a sound with a definite frequency and intensity. With the retardation of electrons and generation of X-rays one might say that there are "bangs", following one after the other. The energy of the X-ray radiation given off with the retardation of each electron represents a certain "quantum", or size, depending on the characteristics of the retardation and the rapidity with which the electron loses velocity.

However, in spite of the lack of a periodic process with such retardation, it is still possible to assign a certain wave length to X-radiation, related to the velocity of the electrons as they strike the anode and the rapidity of deacceleration of individual electrons. If this length is compared with the wave length of light, one may say that on the average the wave length of the X-rays is 10,000 times

shorter than that of light. The higher the voltage on the tube, the greater will be the velocity of the electrons when they strike the anode mirror, and the shorter the wave length of the X-rays. The shorter the wave length, the more easily can the X-rays penetrate substance. The properties of X-rays are associated with their short wave length, which distinguish them from light rays. Not all substances are transparent to light, while X-rays can penetrate (to a lesser or greater extent) any substance. It is this property which makes it possible to determine the internal structure of a substance. As with radio waves, X-rays are not perceived by the eye; the former are too long, while the latter are too short to excite our visual apparatus.

At the present time voltages of about 4 to 2000 Kv are being used, depending on the kind of material examined. The higher the voltage the shorter the wave length of the X-rays. The dependency between the wave length of the X-rays and the voltage which produces them is given by the formula

$$\lambda_o = \frac{12.39}{u_{max\ Kv}} \cdot \frac{1}{100,000,000}\ cm \qquad (4b)$$

In order to avoid such fractions, the wave length of X-rays is not expressed in centimeters but Angstroms

$$1\text{Å} = \frac{1}{100,000,000}\ cm = 10^{-8}\ cm \qquad (4c)$$

in which case the formula becomes

$$\lambda_o = \frac{12.39}{u_{max\ Kv}}\ \text{Å} \qquad (5)$$

If we substitute the number of kilovolts applied to the ends of the tube for U in the equation, the appropriate wave length is obtained.

Thus with the indicated range of voltages from 4 to 2000 Kv, which is in use at the present time for one or another radioscopic application, the corresponding range of 3 to 0.006 hundred-millionth parts of a centimeter or 3 to 0.006 Å is obtained.

Equation (5) allows, on the one hand, the calculation of wave lengths which will be obtained with a certain working voltage, and on the other determination of the necessary voltage for the production of a minimum wave length. The quality of the radiation depends on the wave length -- on its ability to penetrate a material a certain distance and guarantee a good picture.

It is essential to note that X-rays are produced by the collision of electrons with the atoms of the anode and their retardation in a very thin layer. Electrons may be retarded in various ways: some with shorter and others with longer paths. In this way different impulses, due to the retardation of electrons, will vary in size and correspond to waves of different length. Also, the voltage applied to the tube is usually changing in intensity. (Not only does the voltage vary at the poles of the transformer, but also the sign (direction). The tube can work with such potentials since it does not allow the passage of current when the cathode is connected to the positive pole and the anode with the negative, providing the anode is not heated to white heat. However with equipment that uses more than 100 Kv, a rectifier, the so-called kenotron, is used before the tube. Under these conditions the tube does not wear out so fast.) In equation (5) the maximum value of U is used to obtain the wave length λ_o. Therefore, λ_o is the shortest wave length that may be observed in the group of wave lengths. If the alternating current from the transformer grows from zero to maximum

value, at each intermediate value of U a wave will be produced of the corresponding length. However, it is impossible to produce a wave that is shorter than the one corresponding to U_{max} in equation (5). Thus the spectrum of X-radiation will be quite wide. This type of radiation is called nonunique, or sometimes by analogy with light, "white", or the retardation spectrum. Wave lengths from 3 to 0.006 Å, corresponding to 4 to 2,000 Kv, are the shortest waves obtained with these voltages; they represent the limits of the spectrum produced with the voltages indicated above. Every spectrum also includes longer waves. The most intensive part of the spectrum lies in the wave length region $\lambda_{max} = 1.5\lambda_o$. This region may be called the "working" part of the spectrum.

THE DECREASE IN THE ENERGY OF X-RAYS AS THEY PASS THROUGH A SUBSTANCE

X-rays differ from light rays in their ability to penetrate objects which are opaque to light. This does not mean, however, that they pass with equal ease through any object of variable thickness. The difference in the transparency of different thickness and materials to X-rays is the very thing which allows the discovery of irregularities in a material, its inner defects. Radiographic examination for the determination of defects in objects is based on the law of the decrease of X-ray energy.

On passing through any substance some portion of the energy is lost, and the wave group leaves weakened. Part of the energy is lost to absorption by the substance, part is scattered in all directions by the molecules and atoms of the substance (as happens in the scattering of light by clouds, cloudy fluid media, or in general bodies which do not have the ability to reflect light, as

for instance, a mirror).

The scattered portion of the wave group can be "found", if a suitable instrument is used to study all the regions surrounding the point which was struck by the wave group from the tube (the so-called primary radiation).

The total effects of scattering in various directions, using this instrument, must amount to the total scattered portion of the primary radiation.

Determining the portion of the primary radiation "lost" by absorption is more difficult, since this part of the energy is transformed into other forms of energy, which may be of several types. The absorbed energy may change into: (a) energy of electrons freed in the substance; (b) electrical energy; (c) chemical energy; (d) radiant energy; and (e) thermal energy.

Not all of these transformations take place with each absorption of a primary quantum, since they not only depend on the quality of the radiation but also on the composition and properties of the absorbing material.

(a) Free electrons (or Beta-radiation) are always present with the absorption of X-rays. Part of these electrons (the so-called photo-electrons) leave the radiated object, while another part, which give up their kinetic energy to the atoms and molecules of the object, lead to the direct production of other forms of energy (electrical, chemical, radiant, thermal), which are the final products of X-ray absorption. In a living organism Beta radiation causes various biological processes.

(b) The electrical effects of X-rays are apparent in the appearance of electro-conductivity in a number of materials (gaseous, as well as liquid or solid) which were nonconducting before radiation. This is the so-called effect of ionization, which is particularly easy to detect in gases and is one of the methods used for measuring the energy of X-rays.

(c) Chemical reactions (which in this case are called photochemical, i.e., initiated by radiation energy) are only produced in materials with a suitable chemical composition, as in the emulsion of a photographic film or plate. A film will darken on being developed after exposure to X-rays. Other examples of a photochemical reaction are the formation of calomel from a mixture of mercuric chloride and ammonium oxalate, the formation of iodine in a 2 percent solution of iodoform in chloroform, and others.

(d) Radiant energy produced as a result of X-ray absorption may arise as the light of luminescence (luminescence is taken to mean "cold" light, not associated with a rise of temperature of the luminating object), as in the case of certain minerals or salts used to coat X-ray screens for radioscopy and intensification, and also as secondary X-ray radiation, which has a wave length characteristic of the exposed substance, known as the characteristic radiation.

(e) There is always some conversion of X-ray energy into heat, but the amount producedis so small that it can only be detected in specially designed experiments which make use of very sensitive instruments.

All of the listed forms of energy except (a) are tertiary effects, observed because of the absorption of X-rays. If the

X-ray beam striking the substance is considered the primary effect, the secondary effect it produces is the release of photoelectrons (a). The latter, giving up their kinetic energy to the atoms and molecules with which they may collide, may give rise to the tertiary effects, the remaining listed forms of energy (b, c, d, e).

Figure 6 is a schematic representation of the energy transformations of X-rays which have been discussed.

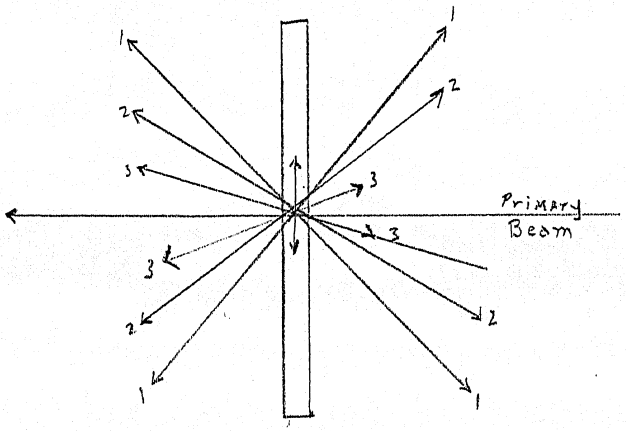

Figure 6. Diagram Illustrating the Formation of Different Types of Secondary Radiation: 1 -- Scattered Radiation; 2 -- Characteristic Radiation; 3 -- Photo-electrons (Beta-radiation); 4 -- Heat.

THE LAW OF THE DECREASE IN ENERGY OF X-RAYS

The amount of energy loss (absorption and scattering) depends on the quality of the radiation (spectral characteristics), thickness of the absorbing material, and its chemical properties.

The Dependency of Loss on the Thickness of the Material

As both theoretical considerations and many experiments have

shown, the decrease of X-ray energy in a substance is not proportional to the thickness of the material.

In order to determine the wave length the following relationship is observed: in layers of identical thickness and with the same composition, the same portion of the incident energy will be held back. Let us suppose, that each layer of a particular substance 1 centimeter thick retains 10 percent of the incident energy. If the intensity (by intensity is meant the energy falling on an area of 1 square centimeter perpendicular to the beam of rays in 1 sec) at the surface of a material J_o equals 100 units, the first layer will retain 10 units (10 percent), and on leaving it the intensity will equal 100 - 10 = 90 units, or $J_1 = 0.9J_o$. The incident energy on the second layer is $J_1 = 90$ units. Of these 90 units the second layer will again hold back 10 percent or 9 units. Therefore, on leaving the second layer, i.e., after passing through 2 centimeters, the intensity J_2 will be equal to 90 - 9 = 81 units, or $J_2 = 0.9\ J_1 = (0.9)^2\ J_o$. Analogously, on leaving the third layer, i.e., after penetrating 3 centimeters, $J_3 = 0.9\ J_2 = (0.9)^3\ J_o$; on leaving the fourth $J_4 = 0.9\ J_3 = (0.9)^4\ J_o$, etc.

In this way one may note that after passing through layers with a thickness of x centimeters, the intensity of the rays equals

$$J_x = (0.9)^x\ J_o \qquad (6)$$

The ratio of intensities between two successive depths, separated by a distance of 1 centimeter, will be the same, i.e.,

$$\frac{J_1}{J_o} = \frac{J_2}{J_1} = \frac{J_3}{J_2} = \frac{J_4}{J_2} = \frac{J_x}{J_{x-1}} \qquad (6a)$$

In the given example this relationship will be 0.9. Consequently, the decrease of the initial intensity follows the increase of a certain number (equation 6), whose exponent represents the thickness of the material expressed in centimeters.

The Dependency of Loss on the Chemical Properties of the Absorbing Material

In the preceding example we arbitrarily assumed that 10 percent of the incident energy is held back in a ray path falling on a layer 1 centimeter thick. The absorption of energy depends to a great extent on the chemical properties of the substance and also on the quality of the radiation -- its wave length. For this reason, the portion of the energy absorbed in a path of 1 centimeter will differ in various substances, and, depending on the material, the coefficient for energy leaving the layer of thickness x (equation 6) will not be $(0.9)^x$ but a different magnitude. In order to show this function, 0.9 in the parenthesis may be replaced with $\frac{1}{e^{\mu}}$, where e -- is a constant equal to 2.72 (the so-called natural logarithmic base), and μ -- an exponent, whose size depends on the properties of the absorbing substance under identical quality of radiation. This is the so-called linear absorption coefficient for the energy of the X-rays. It indicates what portion of the X-ray energy falling on a layer will be "lost" with the passage of the rays through 1 centimeter of a given substance. In order to determine the size of this coefficient in the example considered above, the coefficient 0.9 may be represented by $\frac{1}{e^{\mu}}$. Equating these quantities, we obtain

$$\frac{1}{e^{\mu}} = 0.9 \qquad (6b)$$

There are tables showing the size of e^{μ} for different μ in literature. Using such a table, μ may be chosen in such a way as to obtain the written equation. In this case the coefficient must equal 0.10. We determined μ as the portion of the energy which will be absorbed by a 1 centimeter layer. A tenth part of any quantity equals 10 percent. In our example we started with this figure, not calling it the absorption coefficient. If we had started with 20 percent instead of 10 percent, the coefficient would be 0.8 instead of 0.9. If $0.8 = \frac{1}{e}$, then μ is 0.2, which equals 20 percent of the incident energy falling on the layer. In this way, by placing the linear coefficient of absorption μ in equation (6), we obtain the general relationship

$$J_x = \frac{1}{e^{x}} J_o \qquad (7)$$

(This equation is usually written with a negative power $J_x = J_o e^{-x}$).

Coefficient μ has been determined many times for various elements, and many-place tables have been compiled for them. They are used for the calculation of absorption according to equation (7). If the coefficient μ has been found from Table 2, for example, the emergent energy from a layer may be calculated by substituting the thickness of the absorbing layer in centimeters for x in the equation.

The calculations in the examples given above were only intended to show the derivation of the final formula (7) by a generalization of individual cases.

The intensity J of the radiation at a given point is proportional to the current strength i in the tube, the atomic number z

of the element which is used for the anode mirror, and the square of the voltage U applied to the tube. With an increase in distance F from the tube, the intensity decreases approximately as the square of the distance. One may write the following equation to show the intensity mathematically $J_0 = \frac{k \cdot i \cdot U^2 \cdot Z}{F^2}$ (8) where k is a certain proportionality constant which depends on measurement units and the design of the apparatus.

If we limit the radiated area to 1 square centimeter and measure the decrease of energy in a layer 1 centimeter thick, the fraction of energy absorbed will not differ in comparison with a certain absorption over a large area, since the same fraction of the incident energy hitting the layer will be absorbed in both cases. In cases where 1 square centimeter is radiated, the linear absorption coefficient may be determined a little differently. Since the absorbing area in this case is 1 square centimeter and the path of the rays is 1 centimeter, the X-rays pass through 1 cubic centimeter of substance. In that case, the linear absorption coefficient μ, showing the fraction of energy absorbed in 1 centimeter, is also the measure of absorption in 1 cubic centimeter of this substance. Since 1 cubic centimeter of various substances contains different quantities, it is more efficient to express the absorption of X-rays not for identical volumes, but for identical quantities of substance. 1 cubic centimeter of any material contains an amount of material which is determined by its density (or specific gravity), i.e., the mass in grams (or the weight of the substance relative to the weight of water). Therefore, if μ gives the fraction of the energy absorbed in 1 cubic centimeter of substance or in ρ grams, dividing μ by ρ gives the absorption by 1 gram of substance. This coefficient is called the mass absorption coefficient $\frac{\mu}{\rho}$. It shows the relation of X-ray absorption to the nature of the particular sub-

stance, and to its chemical properties.

In the tables presented, the absorption coefficients given (as in Table 2) are usually just these coefficients. Their magnitude is very closely related to the atomic number of the element Z in the periodic system of Mendeleyev. The coefficient increases with higher atomic number. In practical radiation work one may assume that the absorption increases with increasing density of material, but not proportional to it.

The Dependency of Absorption on the Quality of the Radiation

As has been indicated above, the ability of X-rays to penetrate a certain distance in a material depends on their wavelength. The shorter the wavelength (i.e., the higher voltage), the deeper will the X-rays penetrate and the "harder" they are; on the other hand, the lower the voltage, the longer and "softer" are the X-rays and the shallower depth they will reach in a substance. Therefore, if we determine the mass (or linear) absorption coefficient for the same element with different wavelengths we will obtain different values of μ or μ/ρ. The tables of coefficients, mentioned before, are compiled for different elements and different wavelengths. Therefore, it is essential to know the working wavelengths for any calculations. At the same time, it is essential to note that radiation spectra are not discrete and that each wavelength making up a particular spectrum will be absorbed differently according to the indicated dependcy of the absorption on the wavelength. In order to calculate the absorption one ought to take some kind of average wavelength and use the tables to get the corresponding absorption coefficient. An orientation calculation may be made with a wavelength $\lambda_{MAX} = 1.5\lambda_0$, where λ_0 is found from the working voltage according to equation (5).

X-rays are weakened partly because of absorption and transformation of this energy into other forms of energy and partly by scattering. Thus the coefficient which we have determined includes two coefficients: the coefficient of absorption or transformation τ and the scattering coefficient σ. The linear coefficients τ and σ and mass coefficients $\frac{\tau}{\rho}$ and $\frac{\sigma}{\rho}$ are also distinguished. The first two give the fraction of absorbed (transformed) and scattered energy in 1 cubic centimeter of substance; the second two correspond with the fraction of absorbed and scattered energy in 1 gram of substance.

Therefore one may write $\mu = \tau + \sigma$

$$\frac{\mu}{\rho} = \frac{\tau}{\rho} + \frac{\sigma}{\rho} \qquad (9)$$

In heavy metals (steel, iron, copper, bronze, zinc, lead) τ and $\frac{\tau}{\rho}$ are considerably greater than σ and $\frac{\sigma}{\rho}$. In light alloys τ and $\frac{\tau}{\rho}$ are relatively smaller, while σ and $\frac{\sigma}{\rho}$ do not differ greatly from their values in heavy metals. With an increase in voltage, coefficients τ and $\frac{\tau}{\rho}$ rapidly diminish, while the scattering coefficients decrease to some extent. Generally, σ and $\frac{\sigma}{\rho}$ depend less on the wavelength and atomic number of the substance absorbing the X-rays than τ and $\frac{\tau}{\rho}$. As a result of this, any great change in the coefficients of loss μ and $\frac{\mu}{\rho}$ with a change in wavelength λ (i.e., a change in voltage) or in composition of the absorbing substance depends mainly on a change in the coefficients τ and $\frac{\tau}{\rho}$ (see equation 9).

Finally we present as an example Table 2 which gives the mass absorption coefficients for several elements and wavelengths. The mass scattering coefficients $\frac{\sigma}{\rho}$ are shown below.

The mass scattering coefficients σ/ρ for some elements:

Element and its Atomic Number in the Mendeleyev System		Wavelength λ = 0.2-0.7 Å σ/ρ
C	6	0.180
Al	13	0.180
Fe	26	0.25
Cu	29	0.29
Zn	30	0.30
Sn	50	0.68
Pb	82	0.70

TABLE 2

MASS ABSORPTION COEFFICIENTS μ/ρ FOR CERTAIN ELEMENTS AS A FUNCTION OF WAVE LENGTH λ'

Element		Wave Length λ in Å									
Atomic Number*	Name	0.02	0.05	0.07	0.1	0.15	0.2	0.5	0.7	1.0	Density of the Absorbing Element in g/ cm^3
[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]	[9]	[10]	[11]	[12]
6	Carbon -- C	0.0794	0.1135	0.136	0.1419	0.1592	0.1741	0.3357	0.605	1.402	2.25 (graphite)
12	Magnesium Mg	--	--	0.140	0.152	--	0.250	1.52	4.30	--	1.74
13	Aluminum Al	0.1767	0.1112	0.143	0.156	0.199	0.279	1.90	5.22	13.95	2.65 - 2.80
26	Iron -- Fe	--	0.140	0.202	0.265	--	1.10	14.0	38.5	--	7.85 - 7.88
29	Copper Cu	0.0739	0.1255	0.232	0.3018	0.7180	1.495	19.25	51.0	126.9	8.30 - 8.95

[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]	[9]	[10]	[11]	[12]
30	Zinc -- Zn	--	0.155	0.250	0.325	--	1.76	21.0	58.0	--	6.90 - 7.19
50	Tin -- Sn	0.0544	0.32	0.614	1.17	--	6.10	--	--	87.0	6.97 - 7.30
82	Lead -- Pb	0.0944	0.5403	1.315	3.90	--	4.535	55.74	--	--	11.34

* According to the Mendeleyev Table

1. The linear absorption coefficients μ used in equation (7) are obtained from the coefficients $\frac{\mu}{\rho}$ given in this table by multiplying them by the density ρ of the appropriate absorbing elements.

METHODS OF RECORDING FLAWS DISCLOSED BY RADIOSCOPY

The possibility of disclosing internal defects by the use of X-rays is based on their energy loss laws. At the same time, the action of X-rays on a substance, when they are absorbed by it, allows recording the results of radioscopy by one or another method; in essence, the results of the unequal passage of X-rays through different parts of the examined material or production item.

At the present time, 3 methods for registering defects in materials are known: photographic, visual (on a fluorescent screen) and ionizing. The most widely used of these methods, so far, is the photographic.

Photographic Method

The examined object O is placed in the path of the rays emanating from the focus ϕ of the anode of tube T, with the photographic film P behind it. On passing through parts of an object of different thickness or of material with different density, the X-rays will be weakened to a different extent in their path. Therefore, on reaching the photographic emulsion they will have different intensities in different places, and the strength of their effects will be correspondingly different. After the film is developed, areas of different darkness are obtained, i.e., of varying photographic density. These more or less dark and light areas on the negative are the straight-line projections of the points A, B, C....etc, on the object. On the basis of the density pattern obtained, appropriate conclusions are drawn.

The main diagram of the arrangement of the various parts of the installation is presented in Figure 8. The X-ray tube T, whose

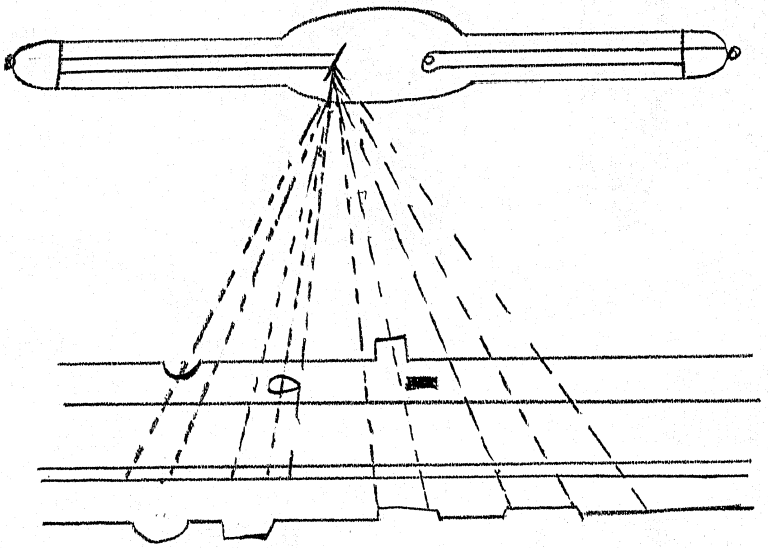

Figure 7. Schematic Representation of the Volume Projection Obtained on Film of a Radiographed Object: P - film; the thickness of the crosshatched region represents the degree of darkening on the negative (film) at the corresponding point; ϕ - tube focus; O - object; A and F - boundary rays of the cone; B - a depression in the surface of the object; C - a less dense inclusion in the object; D - a thickened part of the object; E - a more dense inclusion; K - diaphragm.

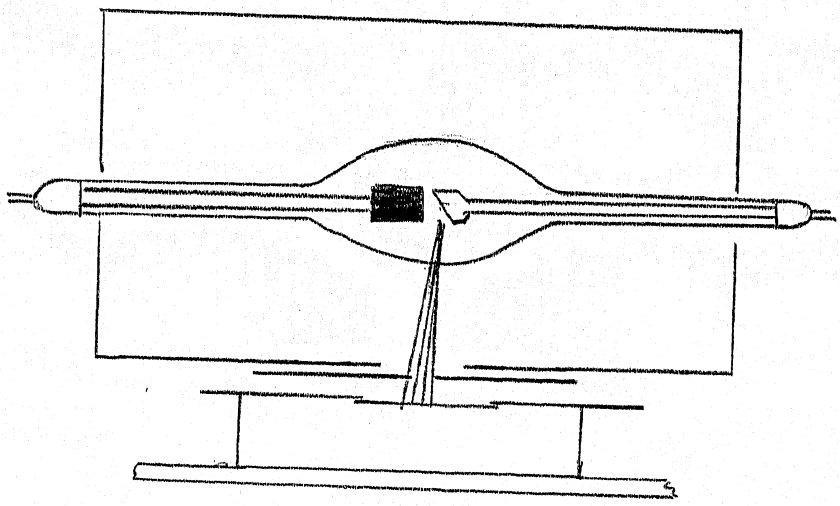

Figure 8. General drawing of the installation of tube and object with radioscopy.

poles are connected to the secondary coil of the transformer, is placed either in a protective housing K, or in a supporting holder without particular shielding in a special enclosure. The rays R, passing through the limiting diaphragm D, hit the examined object O in the form of a cone. Some of the rays, which should not pass through, but enter with the cone, are shielded with sheets of lead Cv'Cv". An aluminum cassette with the photographic film is placed behind the object (as close as possible to it). Sometimes the shape of the member does not allow using a flat cassette and the film has to be held simply in a black-paper envelope, which in some cases may be placed inside the object, as in a tube, cylinder, cavity, etc. Lead sheets are placed behind the cassette or envelope to protect it from scattered radiation, which may reach it from behind (below), as for instance from the table. (Lead, like other heavy metals, strongly absorbs and causes little scattering of X-rays, in contrast to wood, which is a weak absorber and causes relatively great scattering.) decreasing the quality of the picture.

Figure 7 shows that the effects of the object on the radiation passing through it, produced by its irregularity (its varying thickness and density), should be recorded as accurately as possible on the film. What are the requirements for a film that determine its quality? First of all, the photograph should have as much contrast as possible, i.e., the difference in darkening (photographic density) of adjacent areas, which are struck by radiation with a small difference in intensity, should be as great as possible. Secondly, there must be accuracy (sharpness) of reproduction in the film. Put another way, sharply defined contours in the object should not be blurred or indistinct in their representation. These two properties of films -- contrast and sharpness -- depend on the following factors:

(a) hardness of the rays (voltage);

(b) presence of scattered radiation;

(c) the size of the tube focus and its distance from the film;

(d) photo technique.

(a) As a rule, the "softer" radiation gives better contrast, allowing the exposure of smaller defects. But because of the greater absorption in this case (i.e., with the use of lower voltages), the exposure has to be greater than with "hard radiation" (higher voltage) to obtain the same density on the film. Thus the most desirable conditions for obtaining contrast mean inefficient conditions with regard to the economy of the production method. In usual plant practice, with a serial radioscopy of the production, the exposures do not exceed 10-12 minutes with a current strength of 5 milliamperes. For this reason, one often has to neglect the exposure of very small defects, for the advantage of continuous testing. Experience with radioscopy has made it possible to establish certain average regimes, which are given by so-called exposure curves. These are graphs in

which the horizontal curve (abscissa) shows the thickness of the examined material (or primary material of an alloy) in millimeters, while the vertical axis (ordinate) gives the exposure, with a certain voltage. (Exposure is taken to mean the current strength in the tube times the seconds or minutes duration of the exposure; i.e., the exposure is measured in milliampere-seconds or milliampere-minutes. If the ordinate axis gives the exposure, its duration can be obtained by dividing the number of milliampere-seconds or milliampere-minutes by the current strength which is going to be used for making the picture).

A series of such curves, plotted for different voltages, allows choosing the one which gives the lowest suitable voltage for a given thickness of examined material within the allowable limits of exposure, on the one hand, and helps to obtain the greatest contrast, on the other.

Figures 9 and 10 are two examples of such curves, for aluminum and steel. The curves available in the literature sometimes show considerable divergence; this is explained by a lack of identical working conditions. During its work, each laboratory usually determines the optimum conditions for the apparatus and photographic materials which it uses.

(b) Scattered radiation should be avoided as much as possible, since it lessens the quality of the picture, giving extra haze which decreases contrast. It is impossible to eliminate this undesirable secondary radiation, but its harmful effects can be decreased by certain measures. It is more apparent the thicker the radiographed object and the greater the radiated area. The presence of scattered radiation causes a decrease in the sensitivity of the method. The

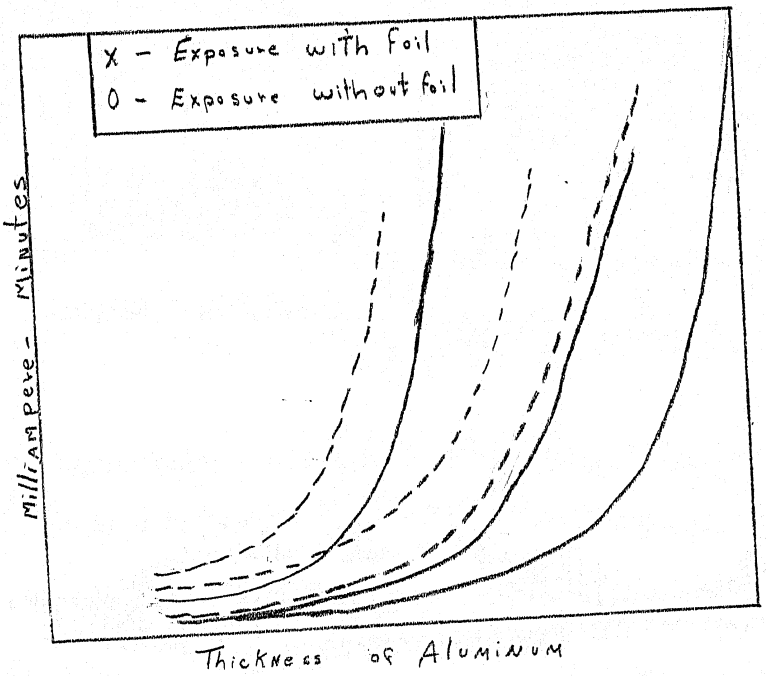

Figure 9. Exposure curves for aluminum. Ordinate: MA minutes; abcissa: thickness of aluminum. Solid line: exposure with foil; broken line: exposure without foil.

absolute size of defects which can be detected increases proportionately to the thickness of the item. The object should be radiographed using areas as small as the operating method allows. This is carried out by limiting the beam of rays (with a diaphragm) coming from the tube and shielding those parts of the item which are not essential from the standpoint of containing faults, but fall in the cone of the beam of rays. The use of filters or foils decreases markedly the undesirable action of scattered radiation.

(c) The third factor which influences the quality of the picture -- the size of the focus and its distance (F) from the film -- affects the accuracy (sharpness) of the reproduction, which depends on the size of the focus and its distance F from the film. The smaller the focus the clearer and sharper will be the figure on the film. With a given focus, the sharpness increases with increasing distance of the tube from the film.

However, increasing this distance also decreases the intensity of the radiation in proportion to the square of the distance (see equation (8)) and requires an increase in the duration of the exposure. Under ordinary conditions, for testing production goods, the focusing distance is made no smaller than 1.5 d, where di is the diameter of the radiographed field. In the radioscopy of large fields or a large number of components, the focusing distance used in practice often reaches 100-200 millimeters. The choice of distance depends on the object of the tests. (Figure 10.)

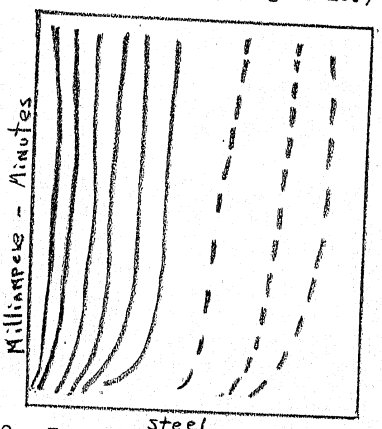

Figure 10. Exposure curves for steel. Solid line -- without shielding; broken line -- with shielding. Ordinate: MA minutes; abcissa: steel.

The tubes in use for radioscopy at the present time have a focusing area of several square millimeters, but tubes are available, constructed for special purposes, requiring high figure sharpness, which have a circular focus diameter of 0.1 to 0.2 millimeters.

(d) The last factor which is important for guaranteeing good pictures is the photographic process and the quality of the film. Photographic processing is taken to mean the technique of handling the film as it has been exposed. The importance of this stage of radiography makes it necessary to go into more detail.

When X-rays penetrate a substance, only the absorbed fraction of energy may cause any effect. Therefore, of the X-ray energy falling on the film, having passed through the examined object, only that fraction which is absorbed in the light-sensitive emulsion can act on the film. For this reason, in order to get stronger action, it is essential to prepare the film in such a way that it absorbs rays to the greatest extent possible. This is usually accomplished by making its emulsion layer thicker than in ordinary photographic emulsions, and also applying the emulsion to two sides. This not only increases the absorption of rays in the emulsion, but also the observed contrast of the negative after development. The energy absorbed by the film has a primary action on the emulsion, causing the appearance of the so-called latent (invisible) image. This takes place when there are certain changes in the silver bromide of the emulsion. Separate centers are created in the form of tiny particles of metallic silver. These centers are subject to the successive process of development, with the result that under the influence of the developer metallic silver is precipitated from the silver bromide of the emulsion in large quantity, in those places where the previous ra-

diation had caused the formation of centers or nuclei (as mentioned above). Thelast parts of the film to darken are those where the X-rays did not fall, and silver nuclei were not formed.

The difference in the density of the precipitated silver after development produces the observed contrast in the image. The speed of development depends on both the quality of the developer and its temperature.

It is essential to fix the developed image, so that with subsequent exposure, light will not act as a developer on the remaining, unchanged silver bromide. Fixing amounts to dissolving the remaining silver bromide with the fixing solution. The silver salts formed with the fixative are easily soluble in water and are removed by washing the negative. Precipitated silver, in a lesser or greater density, depending on the formative action of the X-rays, is now the only thing which remains. This density is responsible for the lesser and greater blackening of the different parts of the negative.

The photographic density (darkening) can be measured with special instruments, so-called photometers or densitometers. If ordinary light of an intensity J falls on a negative, a density D = 1 is observed if the relation $J/J_o = 0.1$. If there is weakening of the light by 100 times, i.e., with $J/J_o = 0.01$, the density D = 2; with $J/J_o = 0.001$, D = 3, etc. With a weakening of less than 10 times, or with a weakening between 10 and 100, 100 and 1000, fractions with the following values are obtained: $D < 1$, $D < 2$, $2 < D < 3$, etc. Such standard densities (darkenings) can be obtained by using films illuminated for various periods of time. The normal negative density after exposure is considered to be in the range of 0.8-1.2, on the average. In the testing of magnesium alloys, small defects are shown better with

a relatively great density, as high as D = 1.5 2.5. The density of the negative may be increased either by increasing the intensity of the X-rays striking the film (i.e., by increasing either the voltage or the current strength), or by increasing the duration of the exposure.

X-ray films are processed by the same methods used in ordinary photography, with the exception that in X-ray photography it is insistently recommended that the film be kept in the selected developer a definite length of time, and the darkness not determined with the eye. In this case, with good primary work, the treatment of the film may easily determine or eliminate the reasons for unsuitable pictures.

In X-ray radiography, high-speed, contrasty developers are usually used, most often methyl-hydroquinone. Formulas most suitable for a particular type of film are usually given by the factory which makes the film and are enclosed in the packages.

At the present time in the USSR, plants are producing films of 2 types: "X" X-ray films, intended for exposures with intensifying screens, and "XX" or "2X" films, for work without screens. The former must be used in the radiography of steel objects of a thickness greater than 12-15 millimeters and lighter alloys of great thickness. The latter may be used with steel of lesser thickness and in most cases with light alloys. Type "X" is also useful for work without screens.

When it is desired to obtain great image detail and strong contrast, as, for example, for revealing very small faults in objects, a film is used that has decreased sensitivity, but very fine grain and high contrast. Pictures obtained with such film may be magnified 10 to 20 times, and with special emulsions up to 50 to 200 times. Such pic-

tures are obtained, for example, in micro-radiography, when it is necessary to compare enlarged X-ray pictures with pictures of etched sections obtained with metal microscopes. A picture from a metal microscope gives an idea of the structure of the surface of the metal only, while the X-ray picture, obtained from a thin film of the same alloy, gives a supplementary volume picture of the structure of the examined material. Sharp-focus tubes are especially useful for these pictures.

The Use of Intensifying Screens

As has been discussed above, excessively long exposures, in the first place, are economically undesirable, and, in the second place, lead to a lowering of picture quality due to fogging caused by scattered radiation. Therefore, so-called intensifying screens are used to cut down exposures. These screens are a sheet of cardboard which has been coated on one side with an emulsion sensitive to X-rays, basically composed of certain salts (for example calcium or cadmium tungstate), which become luminescent when acted upon by X-rays.

The film is placed between two such screens, with their emulsions tightly in contact with the film on both sides. All this is placed in a cassette, which is placed under the radiographed object as usual. During the exposure, the X-rays cause luminescense of the emulsion to become stronger, as the intensity of the radiation becomes stronger. The light produced by luminescense of the screen strongly influences the film and causes its darkening beyond that caused by the X-rays. This additional light from the screen also shortens the exposure, which averages 10 times less with its use than without. With the same voltage, the most important requirement for working with screens is that they be tightly placed against the film; if this is not observed there is a scattering of light and blurring of the image

on the negative. One must note, however, that no matter how tightly the screens are placed against the film, the sharpness that would be obtained without the screen cannot be realized, because of the relatively large grain of the screen emulsion. For this reason, one cannot count on exposing such small flaws with a screen as may be detected without it. However, with the radiography of great thicknesses, their use is unavoidable, unless one makes use of large increases in voltage, in which case, however, as explained above, there is decrease in contrast.

Besides the intensifying screens we have discussed, there is a wide use of tin and zinc foils from several tenths to several hundredths of a millimeter thick, depending on the voltage. The cassette is loaded the same way as with the screens. The two foils are placed tightly against the film. The foils have a dual action. First of all, they shorten the exposure by 2-3 times in comparison to that without the use of screens or foils (see Figure 9). Secondly, they filter some of the scattered radiation and thus improve the quality of the picture.

The intensifying action of the foils is due to Beta radiation, i.e., the release of photo electrons by them under the action of X-rays. These photoelectrons produce supplementary photochemical reactions on hitting the film emulsion; i.e., they produce a darkening of the film, after development, beyond that produced by the X-rays.

The Sensitivity of the Photo Method

The exposure of defects by the use of X-rays, even with conditions such that a good picture is obtained, depends on the limits of sensitivity of the photo method. A quantitative evaluation of the

sensitivity may be given by the size of the smallest defect which may appear on the picture. Here the size of the defect is taken to mean its thickness in the direction of the rays. This thickness is usually given as a percent of the overall thickness of the radiographed material. It is impossible to define the sensitivity of the X-ray method by any one figure. It depends on many factors, as, for example, the nature of the defect (pores or cracks, the inclusion of some material, etc), the composition of the substance and its thickness, and the working conditions (high or low voltage).

If the type of defect is not taken into consideration and one discusses only the exposure of differences in the thickness of the material, an approximate understanding of the sensitivity of the method may be obtained from the following data: with the radiography of steel 5 millimeters thick, under average working conditions and without the use of screens, the sensitivity is about 2-2.5 percent. This means that one can expose differences of 0.1-0.125 millimeters in the thickness of such a steel plate. Smaller differences will not be exposed under ordinary conditions. With a thickness of 20 millimeters, one can count on a sensitivity of 1.5 percent with steel, i.e., on the exposure of differences of thickness equal to 0.3 millimeters. With an increase in steel thickness to 30-50 millimeters, the sensitivity stays practically constant and equals 1-1.5 percent, though the absolute difference in thickness, i.e., expressed in millimeters, becomes greater. Thus, for example, with a steel thickness of 50 millimeters a difference of 0.5-0.75 millimeter may be exposed. The data for aluminum is somewhat different: with a thickness of 2.5 millimeters the sensitivity is 7-8 percent, i.e., differences of thickness of 0.175-0.2 millimeters can be exposed; with 5 millimeters, 4.5 percent, or 0.225 millimeters; with 10 millimeters, 3 percent or 0.3 millimeters,

and with 30 millimeters, 2 percent or 0.6 millimeters.

One may ask why aluminum, which may be radiographed with relatively "softer" radiation, shows less sensitivity to the exposure of defects than steel. Let us observe the difference in contrast between two thicknesses. The difference between these thicknesses, produced by an inner air space or the configuration of details, will give a certain contrast which depends on the difference in the density of air and aluminum. The density of air or gas is not so different from aluminum (density 2.7) as it is from steel (7.8). Therefore, the contrast of rays passing through air and metal will be greater in the case of the radiography of steel. In order to obtain the same contrast in both cases, the layer of air in aluminum must be somewhat thicker than in steel, i.e., the exposable difference in the thickness of aluminum has to be greater. In the radiography of magnesium alloys, the density of the magnesium (1.74) is even closer to the density of air than aluminum. The contrast in this case will be still less. It is usually more difficult to expose slight porosity and friability in the radiography of magnesium alloys than in aluminum.

The data presented above on the sensitivity of the X-ray method was obtained by the use of wire standards. It cannot be applied directly to the exposure of various defects, since this exposure depends to a large extent on the chemical composition which determines the density, and the form and location of the defect. The sensitivity for the exposure of various defects will be less than the sensitivity for the exposure of artificial defects because of the difference in standards. For instance, according to the data of some authors, the sensitivity for the exposure of wires of various diameters made of the same material as the radiographed object, placed at its surface, is about 200 percent

greater than the sensitivity for the exposure of air bubbles in the object. Put in another way, air bubbles which may be exposed will have a diameter 3 times greater than the diameter of an exposable wire. Standards with cylindrical openings (which are more similar geometrically to air bubbles than wire), give a sensitivity 20 percent greater than that for the exposure of bubbles. In this way, if one can expose an opening of 1 millimeter in diameter on the film with the use of such a standard placed on the object, one can count, on the average, on exposing air bubbles with a diameter of 1.2 millimeters in the object.

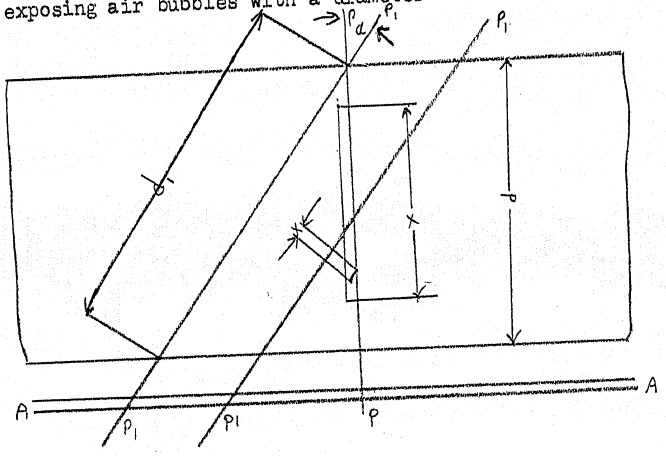

Figure 11. Schematic Representation of the Radioscopy of Fissures at Different Angles.

In spite of the inexact (though approximate) conclusions about the sensitivity of a method by the use of standards, their use is very desirable. The evaluation of pictures made with sensitivity standards allows one to judge the quality of photographs and strive for their improvement. Standards are objects which indicate the quality of the pictures obtained, and the correctness of the selected working regime and phototechnique.

It is more difficult to expose such defects as fissures. They present some differences from other defects with regard to their exposure. Let us define a planar fissure in the plane PP, passing through the surface of the crack in the metal (Figure 11). The sensitivity for detecting this defect is strongly dependent on the angle α, formed between the central ray of the beam from the tube and the depth and width of the fissure. We will present the sensitivity of the method as the difference in the thickness of material which may be resolved. When we radiograph a thickness of material d with a fissure of depth x in the direction PP, i.e., along the plane of the fissure, the rays will pass through a thickness of sound material d-x and a layer of air (or gas) of thickness x. In adjacent sound material the thickness traversed by the rays is d. In this direction of radioscopy we have the maximum thickness x, weakly absorbing the X-rays, with the consequence that the contrast on film A-A will be maximum. With the rays directed along P_1P_1 the thickness of the air layer will only equal x_1 with a passage through a thickness d_1 of sound material Consequently the percentile relationship $\frac{x_1 \cdot 100}{d_1}$ will be notably less than $\frac{x \cdot 100}{d}$ and the contrast in this case may be so small as to not be discernable to the eye, i.e., the fissure will not be exposed.

Thus we see that the exposure of a fissure is strongly dependent on the angle between the rays and the angle of the fissure. For the best exposure it is essential to direct the central rays along the plane of the fissure. If the direction of the fissure in the material is unknown, choosing this angle becomes impossible, with the consequence that in a series of instances fissures may be unexposable. The greater is the depth of the fissure x, the more easily is it exposed. The width of the fissure also plays an important role. The wider the fissure, the greater may be the angle between the rays and its plane PP, with

resolution. Fissures which do not produce a sufficient gap between the fractured surfaces may not be exposable even with optimal radiation direction, i.e., along PP, especially when the fissure has a zig-zag shape. The minimum thickness of a fissure which can be exposed must not be less than several hundredths of a millimeter with optimal ray direction. Hairline cracks are not exposable by X-ray radiography. If two metal blocks with polished vertical surfaces are put face-to-face tightly and radiographed along the direction of the contact surfaces, a separation line will not show on the film. However, if a sheet of paper is put between the flat surfaces, a more dense line will appear on the film. Thus "adherent" metal may not be discovered by radiography.

If a sharp-focus tube is used, which gives a very accurate image, one can get a picture on fine-grain film that can be enlarged optically, by the usual photographic techniques. 15-20 times enlargements of artificial cracks 0.018 millimeter wide and 0.02 millimeter from each other are sufficiently sharp for their exposure with the naked eye.

Limits of Thickness in Radiography with X-Rays

In principle it is possible to radiograph any thickness, but in practice there are certain limits, which are determined both by the magnitude of voltage and duration of exposure. Also, there are limits on the exposure of defects.

Certain calculations show that an increase in exposute from 10 to 60 minutes, i.e., an increase of 500 percent, allows an increase in thickness of only 17 percent.

Table 3 gives the thickness of some materials which can be radiographed with 200 kilovolts and 15 milliamperes with small fields, (fields of less than 5 square centimeters included within the cone of rays), and with fields bigger than 100 square centimeters for aluminum, and bigger than 50 square centimeters for copper and iron. The sizeable supplementary darkening effect with large fields depends on the action of scattered radiation (reducing the quality of the picture). With 5 square centimeters this action is practically nonexistent. With respect to increased radiographed thickness with increased voltage, some numerical figures have been presented in Table 1; the characteristics of this increase, starting with 150 kilovolts, are graphed in Figure 12. [See Table 3 on following page]

In the radiography of steel thicker than 200 millimeters, it is rational to use X-ray production principles which are embodied in electromagnetic accelerators.

In electromagnetic accelerators, the electrons are acceler-

TABLE 3

ORIENTATION LIMITS FOR RADIOGRAPHY OF CERTAIN MATERIALS WITH 200 KILOVOLTS AND 15 MILLIAMPERES, USING TWO INTENSIFYING SCREENS

Element	Duration of Exposure			
	10 min	60 min	10 min	60 min
	Small Field		Large Field	
Aluminum	210 mm	245 mm	325 mm	378 mm
Iron	54	64	69	80
Copper	34	40	40	50

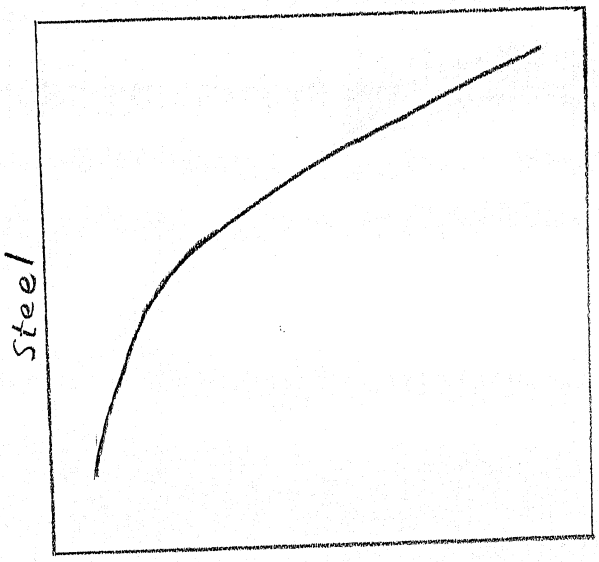

Figure 12. Limits of Thickness of Steel which Can be Radiographed with Various Voltages

ated when they move along the force lines of an electromagnetic field.

Such apparatus has been built for giving electrons 200-250 million electron volts of energy. With these velocities the coefficient of useful action of the electron energy, i.e., the corresponding production of X-ray energy, is much greater than the few percent which we mentioned earlier. For example, with an electromagnetic accelerator of 20 million electron-volts, the production of X-ray radiation amounts to 65 percent of the energy of the electrons, and only 35 percent of the latter is used up in producing heat. In order to give electrons similar energies in X-ray tubes using transformers (analogous to the apparatus used for 1 and 2 million volts) equipment of large weight and bulk is required.

A Visual Method of Observing Defects (Fluoroscopy)

In the visual method of checking parts the image of the radioscoped object and its defects is obtained on a fluorescent screen, placed behind the examined object instead of a film. In this case one makes use of the action of X-Rays (to be more exact, photoelectrons which are released in the substance by the X-rays) on certain salts which fluoresce under these conditions. Fluorescent screens do not differ in principle from intensifying screens; they too are a sheet of cardboard which is covered on one side with a salt sensitive to X-rays. Their chemical composition is a little different than that used in intensifying screens. In the latter case it is necessary to have light to which photographic emulsions are particularly sensitive, i.e., blue-biolet. With the visual method, on the other hand, light is needed to which the eye is very sensitive. This part of the spectrum falls in the yellow-green region. Such

light is produced by zinc and cadmium sulfides, which are the main components of the emulsion in such screens.

Fluorescent screens must be as bright as possible with low voltages. The brightness of fluorescence of various parts of the screen depends on the intensity of X-rays in these places. The weaker the absorption of X-rays in the object in front of the screen the greater the brightness will be. Thus, a reverse image is obtained on the screen compared to a film. On a film the greatest darkening is obtained behind the object in those places which absorb the rays weakly, and bright areas on the film are produced behind strongly absorbing parts of the object. The reverse picture is obtained on screens (the same as prints on photographic paper from a negative), i.e., a positive picture. The factors which influence the image quality on the screen are the same as those in the photo method, with the exception of the last process -- the film processing, which is lacking in this case. The quality of the screen itself influences to a large degree the quality of the image. Besides the greatest possible brightness, it is desirable to have a screen emulsion with a fine grain, which increases the sharpness of the image. However, usually, with decreasing grain size the brightness of fluorescence decreases.

The sensitivity of screens is less than that of the photo method with respect to identification flaws. For example, with steel 5 millimeters thick it is 3 times less with a screen; 3.6 times less with 10 millimeters, and 5 times less with 16 millimeters than obtained on film (with evaluation of sensitivity using the diameter of the smallest exposable steel wire). Pores in aluminum

castings of thickness up to 50 millimeters cannot be detected if their diameter is less than 5 percent of the Fluoroscoped thickness. In the case of iron (steel) of thickness to 10 millimeters the diameter of bubbles must be no less than 8 percent. There are some apparent contradictions. In the photo method, the sensitivity is higher with steel than with aluminum; with the visual method it is vice-versa. This is explained by the fact that steel or iron absorb X-rays much more strongly than aluminum. Therefore, the luminescence of a screen behind steel will be much weaker, and the eye will be unable to note small inclusions, since the exposure of defects depends on brightness.

The average sensitivity, if it is determined not by depth (thickness), but visibility of the diameter of individual air inclusions on the plane of the screen (with an aluminum alloy, a thickness of 6-15 millimeters), may be expressed as 10-15 percent of the fluoroscoped thickness.

Sharp-focus tubes, which have been discussed above, allow obtaining enlarged images of defects in objects by placing the screen at a more considerable distance from the fluoroscoped object. With this technique the sensitivity to the detection of defects on a screen is increased. The thickness which may be fluoroscoped with a guarantee of exposing small defects is much less than with the photo method. For instance, good results cannot be obtained with light alloys thicker than 40-50 millimeters and steel thicker than 12-15 millimeters. This depends on the inadequacy of screen brightness with the fluoroscopy of great thicknesses. Increasing the voltage to produce greater brightness, as is known, lowers

the contrast.

The voltages which must be used in the visual method are relatively higher than with the photo method, with the same thickness of material. For example, while 40-50 kilovolts and 5 milliamperes are required for the radiography of a magnesium alloy 4 millimeters thick, 60 kilovolts does not give enough brightness with the screen method and 100-120 kilovolts are required to expose holes 5 millimeters in diameter on a step gauge.

Even though the visual methos is much less sensitive than the photographic one, it still has advantages over the latter in some cases. It is more economical, since there is no expense for film and photo-chemicals, and also more efficient, because no time is spent loading cassettes and processing film. This method is very convenient for a preliminary testing of items for more or less large defects. Such items are immediately discarded and not passed on for further processing. For the detection of small defects or in doubtful cases it is necessary to make a supplementary picture on a film, which also serves as a document for final conclusions about the quality of the item.

This kind of complex method which makes use of both techniques of radioscopy is being used in many plants.

Up to recent times, the lack of documentation was considered a shortcoming of the visual method. The tester sees the defect in the object only while the screen is glowing. As soon as the voltage is turned off, the screen stops glowing and there is no trace on it of an image.

Therefore, a record of the image on the screen can only be obtained with a subsequent picture on film. However, one should note, that the image obtained in this way is not always completely identical with that seen on the screen. Because the film is greatly sensitive, it is possible, on the one hand, to expose smaller defects with it, which were not exposed on the screen. On the other hand, if the position of the object with respect to the direction of the rays was somewhat different in the visual examination than with the photographing, some faults noted on the screen, conversely, may not appear on the film (such cases have been observed), Thus a subsequent photograph is not an exact record of the image on the screen.

The question of documentation with the use of the visual method is solved quite simply with the so-called fluorographic method. Basically this method involves taking a picture of the image of an object or its parts, obtained on a screen, with a photographic apparatus, such as an FED camera. In order to obtain a good picture under ordinary conditions with the radioscopy of metal objects, using a good film, an exposure of several seconds or tenths of seconds is sufficient. The pictures obtained on a 24x30 millimeter frame may be examined with the aid of a projector or enlargements on photographic paper. In the latter case, however, there is some loss of finer detail in the image. If a "fast" motion picture apparatus is used, it is possible to obtain motion pictures of different phases of a process, such as the working of some concealed mechanism, the cooling of molten metal, etc, whose image on the screen changes with time; this can be demonstrated later as an ordinary motion picture.

The photographing of such images on the screen requires "fast" photographic apparatus and film, very sensitive to the light of the fluorescent screen, since its brightness is several times less than the brightness of objects in ordinary motion picture photography.

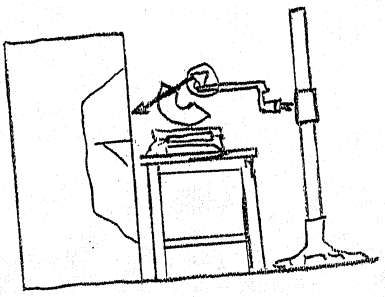

Figure 13. Diagram of a Fluoroscopy Set-up without Mirror.

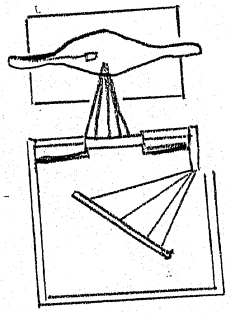

Figure 14. Diagram of a Fluoroscopy Set-up with Mirror.

Figures 13 and 14 show the two principal types of flour-

oscopy setups. Figure 13 shows a set-up without the use of a mirror. The X-rays pass through the object and strike the screen, whose fluorescent emulsion is facing the observer. The latter is located behind sufficiently thick lead glass (this is transparent to visible light, but strongly absorbant X-rays, thus protecting the worker from their harmful action.) The observer stands or sits in the darkened, lead-lined cabinet and looks at the screen through the glass. With suitable mechanisms, located behind the protective shielding, it is possible to rotate or move the object for its examination part by part.

Figure 14 shows a set-up for radioscopy of comparatively small items with the use of a good, ordinary mirror. The beam of rays passes from the tube T, which is in a protective mounting, through the diaphragm D, and on to the object O, placed on a rest G, which absorbs X-rays weakly. Under this rest is located the screen, placed with its fluorescent surface downwards. A mirror S is placed under the screen at an angle. All the components named (except the tube) are within the lead-lined box B. In this arrangement the light rays produced by the screen under the influence of the X-rays (shown in the figure as the short arrows under E) strike the mirror S, and are reflected from it into the eye of the observer. The latter thus sees the reflection of the image on the screen. If control measurements of the intensity of scattered X-ray radiation in the box exceed the tolerance dose strengths, the crack through which the image on the screen is examined may also be shielded with lead glass. These two arrangements are used with considerable variation in practice. It is

especially important here to guarantee good shielding of the worker from X-rays. All movements of the object in front of the screen must be mechanized, if possible, in such a way that the hands of the worker are not stuck by direct or scattered rays.

Apparatus for Very Short Exposures

It would not be entirely correct to call cinematographs, taken from a screen X-ray, motion pictures, since we are dealing in this case with ordinary motion picture photography with the difference that the cinematographic apparatus is not of a photographic nature, but places an image on the screen which changes with time. The radioscopy of the object, in itself, procedes continuously over a considerable period of time, measured inseconds or minutes. X-ray motion picture photography means obtaining images of the object (on the screen or film) during the shortest possible time interval, in order to "fix" an individual moment in a fast-moving process. No motion picture camera is used in this case, and instead powerful, successive X-ray impulses, following one after the other, which allow exposures in the order of magnitude of hundred-thousandths or millionths of a second. This is accomplished with the aid of X-ray impulse equipment. Basically, it does not differ from the usual equipment used in industrial radiography. The difference is that usually the radiation proceeds for minutes with a comparatively low current in the tube, measured in milliamperes, i.e., thousandth parts of an ampere; while with impulse radiography the intensity of the X-rays is increased to the greatest possible values by increasing the current strength in the tube to several hundred

or even thousand amperes. With such intensity the shortening of the exposure time is very considerable. Thus if a picture required 5 minutes exposure at 5 milliamperes, with 200 amperes, at the same voltage, the intensity would increase by $\frac{200 \cdot 1000}{5}$ i.e. 40,000 times, and the exposure can be shortened by approximately the same number of times. Thus instead of 5 minutes, the exposure would be $\frac{5}{40,000}$ minutes $\frac{300}{40,000}$ seconds or approximately $\frac{7}{1000}$ seconds.

This example is not an exact calculation of the relationship between load and exposure duration in impulse radiography. It is only meant to show that if very short exposures are required, it is possible to have very high current strengths in the tube during these instants. Ordinary X-ray equipment cannot give currents with a strength of 100-200 amperes. However, if certain structural additions and the corresponding automatic mechanisms are added to a 100-200 kilovolt apparatus, it may serve for impulse photography. The additions in this case involve connecting auxiliary electric capacity, so-called condensers. These instruments can collect large quantities of electric charge. If such condensers are connected to the secondary winding of a transformer they can absorb sizeable amounts of electric charge, which is stored in them until the moment needed. If the condensers are connected with the tube at the moment when the picture is to be taken, all the charge stored in them passes through the tube in an extremely short period of time and the condensers discharge. The size of the charge stored in the condensers depends on their construction and size, and is a measure of their capacity. The strength of the current is a function of the size of the charge and the speed of its movement through

the cross section of the conductor.

Thus the large charge of the condensers, passing through the tube during a short time, produces a necessarily large current, i.e., hundreds or thousands of amperes, depending on the capacity of the condensers and the voltage with which they are charged. The automatic devices are needed for charging and discharging the condensers at the needed moment, dictated by the character of the photographing process.

Special tubes are made for radiation of this power. It is essential to note that ordinary X-ray tubes, designed for relatively extended loads with small currents, can(within certain ranges of voltage) withstand fairly powerful impulses over short discharge times without being damaged.

Thus, for example, the impulse method is used in medical practice for the X-raying of moving parts in the body, as the heart and lungs, which give a somewhat blurred image on film with ordinary conditions of exposure. An ordinary diagnostic tube, designed for voltages up to a maximum of 100 kilovolts, was used for the pictures. With impulses that lasted from 0.02 to 0.04 seconds it withstood currents of up to 600 amperes strength. This shows that the electrical "durability" of ordinary tubes and kenotrons, with short-duration loads, exceeds by many times their"durability" under ordinary working conditions. Consequently, in many cases where the impulse method is applied, it is possible to use ordinary X-ray apparatus with the addition, basically, of supplementary capacity and corresponding automatic control of condenser discharge.

Ionization Method of Recording
Flaws in Production Items

The ionization method is based on the ability of X-ray to make air or gases electro-conducting during the time of radiation. In order to make use of this property of X-rays, they are directed into a so-called ionization chamber, which is a metal, graphite or bakelite chamber of cylindrical form. The chamber has a small window which is very thin and transparent to X-rays. The rays are directed through this window and pass into the chamber between two metallic electrodes, one of which is grounded, while the other is charged to a voltage of several tens of hundreds of volts (depending on the type of chamber). This is provided from dry cell batteries, electrostatic machines, storage batteries, and sometimes with rectified alternating current from a circuit.

Air or other gas in its normal state does not conduct electricity. But if X-rays are passed between the electrodes of the chamber the gas will becone conducting, and an electric current will pass between the electrodes which can be measured with sensitive instruments (galvanometer or electrometer). The strength of the current in the ionization chamber and reading of the instrument will be proportional to the intensity of the X-rays. [See Figure 15 on following page]

Consequently, if such a chamber is placed behind an examined object, there will be a weaker ionizing current in the chamber if the object absorbs rays strongly. If the object is highly tansparent to X-rays the current in the chamber will be stronger. Figure 15 shows a diagram of such an arrangement.

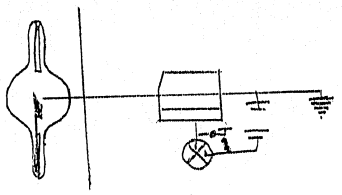

Figure 15. Diagram Showing Arrangement of an Ionization Chamber; T -- X-ray tube; D -- lead diaphragm for limiting the beam of rays; A -- X-rayed wall; I -- ionization chamber; E -- electrometer; B -- storage batteries for the charging electrode C. The wall of the chamber and the other pole of the battery series are grounded.

It is not possible to get a picture of the position of thicker or more dense parts of the X-rayed volume of an item with the use of an ionizing chamber. The chamber and its measuring instrument gi give the summation-of effects of the beam of rays entering the chamber. Using a negative obtained by radiography of an object, one can, for instance, separate two small air inclusions or detect a crack due to air bubbles. This is not possible with the use of an ionization chamber. Whether a certain obtained effect (measured by the strength of the current in the chamber) is due to two air inclusions, next to each other, or one, and whether an increase of ionization current is produced by cracks or air bubbles, is impossible to ascertain. Using a chamber one can only establish if there is

more or less dense material in a certain area than in its surroundings. The usual cross section of a ray beam entering the chamber is rather small (several square centimeters), so the object has to be X-rayed by small fields, moving the chamber along it or shifting the object in front of the chamber. The ionizing method is useful for the examination of smooth items for variations produced, for example, by incorrect internal machining, disconnections, wall corrosions, etc. The ionization method, like the visual, does not require supplementary expenditure of photo materials or time to develop the films, and for this reason it is more economical and often more efficient. With regard to the sensitivity of the method, there is information available about chambers which allow the detection of differences in thickness of percent and sometimes less.

So-called counters, which are also built on the principle of ionization, may have a sensitivity as high as 0.5 percent with an X-rayed thickness of more than 2 millimeters. Ionization chambers yield to counters with regard to their working speed. In spite of the great sensitivity of ionization chambers and counters, and their relatively fast control rate, they cannot wholly replace the photographic and visual methods of flaw detection, since they do not give an overall picture of the form and location of the defects. However, in individual cases they unquestionably have some advantages.

Determination of the Position of Defects and the Thickness of X-rayed Walls

Often it is necessary to determine not only the presence of a defect, but its position, its distance from one of the surfaces of the object. Sometimes there may be a question about the thick-

ness of the walls of some vessel, subject to separation of corrosion, or the uniformity of wall thickness of some component in production.

In many cases the X-ray method may answer these questions, and we will consider briefly the principles on the basis of which the problems presented above may be solved.

Determination of the Position of a Fault

Let us suppose that in a given object ABCD (Figure 16) an air inclusion has been discovered by the X-ray method and it is necessary to determine its distance x from the lower surface.

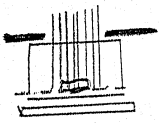

Figure 16. Diagram showing the determination of the position of a fault by two photographs with a rotation of the object.

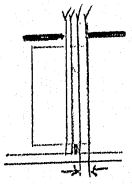

Figure 17.

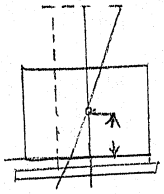

Figure 18. Diagram showing the determination of the position of a fault by two pictures on the same film with a movement of the tube parallel to the film.

In order to answer this question it is necessary to make a second picture of the object after its rotation through 90 degrees (Figure 17). The image of the same defect obtained on the second picture allows measurement of the distance b from the surface CD, which will be approximately (as a consequence of some divergence of the rays and the incompletely tight application of the emulsion of the film to the surface of the object) equal to the sought distance x. This type of method is not suitable for objects of very great thickness in the direction CD, or of complex configuration. In such cases it is necessary to make a second picture with the same position of the object, but with a different position of the tube. After obtaining an image of the defect at E on the film (Figure 18), the casette is loaded with fresh film and two pictures are taken on it, one after the other. The first is with the same position of the tube, while for the second picture the tube is moved a certain distance in the plane parallel to that of the cassette. Let us suppose that in the first picture on the second film the focus of the tube is located at F_o, and the defect is at point O at a distance x from the lower surface of the object, and it is this which is to be determined. Its image will appear at point E. The second film was made after the displacement of the focus of the tube to point F_{oi}, at a distance b from F_o. Then the central ray will give an image of the defect O, at E_1, at a distance a from E. The distance from the focus to the film remains the same in both cases and is equal to F. Now, on the basis of the similarity of triangles O $F_oF_{o_1}$ and O E. E_1 with a very small c, one may write $\frac{b}{a} = \frac{F - x}{x}$, which gives $x = F \frac{a}{a + b}$ (10)

The greater the displacement a and the more exact the measured

distance F from the focus to the film, the more accurate will be the results. With very thin objects the radiation error may be quite considerable. Various localizers are built on this principle. These are fairly simple devices producing the proper results on a scale without special calculations.

Further development of the principle of exposures with different positions of the tube, in order to determine the position of a fault, has been achieved in so-called x-ray steroscopy and tomography. In the first case, a special representation of the position of the defect is obtained on the simultaneous examination in a stereoscope, of two pictures obtained with different positions of the tube. We not only see its width and length, but also perceive its depth. The tomograph makes use of continuous movement of the tube and film, in opposite directions relative to each other, to give a clear image of those faults which all lie in the same plane of the object; those in other planes blurred on the film. Changing the speed of movement of the film relative to the speed of movement of the tube changes the plane in which the faults are clearly visible.

The tomograph got its basic development in medicine, while at the present time it is not widely used in industry because of the complex arrangement of the whole apparatus. In those cases of industrial production where it is necessary to determine the position of faults, the double photograph, whose principle is discussed above, will give satisfactory results with the aid of simple "localizers".

Determination of Wall Thickness

When walls with a thickness of over 5 millimeters are to be

examined, one can use the following method. The surface of the wall, facing the tube, is covered with lead sheets of such a thickness as to shield out the X-rays at the given voltage. A circular opening a millimeters in diameter is cut out in them. The edge of this opening is beveled at an angle of 45 degrees to give a sharp boundary to the image of the aperture on the film. A film wrapped in dark paper is put tightly against the opposite surface of the wall and a picture is taken. With the focus of the tube at point F_o (Figure 19) at a distance h from the front surface of the film, an image of the aperture with a diameter b millimeters is obtained (because of the divergence of the cone of rays). If the sought thickness at this point is x millimeters, using the similar triangles F_oAB and F_oCD we obtain:

$$a:b = h:(h + x), \text{ from which } x + \frac{hb}{a} - h$$

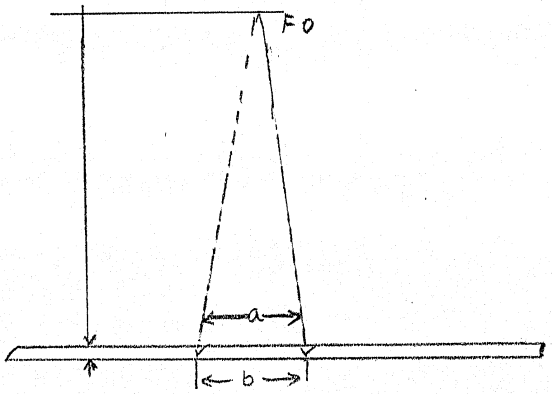

Figure 19. Diagram of set-up for the Determination of Wall Thickness: 1 -- wall; 2 -- lead diaphragm; 3 -- film.

Besides this (inaccurate) method of measuring thickness, other techniques are applied, based on the comparison of the degree of darkening (density) of the negative on special instruments

known as desitometers. In the latter case, the negative obtained from a certain part of the wall is placed under an illuminating lamp arranged for this purpose. The light which passes through the negative emerges more or less weakened, depending on the degree of darkening at a particular place. The light from the lamp which passes through is then usually projected on a photoelectric cell. The latter has the property of producing electric current, when struck by light, whose strength depends on the intensity of the incident light. Thus, dark parts of the negative, which transmit less light, will produce current strength in the photocell which is weaker than that from the lighter parts, which transmit more light. The current strength in the photo cell may be registered with some kine of measuring instrument, such as a very sensitive ammeter, known as a galvanometer. The current strength shown by the galvanometer, while the negative is moved under the light over the photo cell, may be recorded automatically in the form of a curve on photosensitive paper.

If we are examining the changes in wall thickness of an object in some particular direction, we must also move the image of the wall in this direction, i. e., the negative over the photo cell. Having obtained the curve of changes in current strength along some direction of the negative, it is easy to determine at what distance from the starting point there was a decrease in current, i.e., a thinner part of the wall (greater density of the negative). The shape of the curve also shows the character of changes in thickness; whether it changes suddenly or gradually and in what places. If, furthermore, one has a zero line for reading on the measuring instrument, the size of variations from normal wall

thicknesses, it is possible to obtain the thickness of the wall in millimeters at each point along the examined direction.

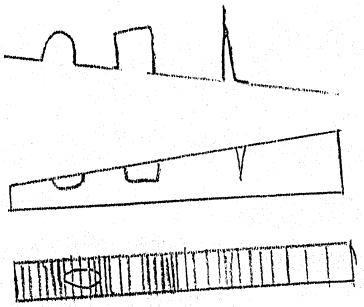

Figure 20. Determination of Wall Thickness with the Use of a Densitometer: a -- diagram of the roentgenogram of the wall; b -- a vertical section through the wall along I - II; c -- densiogram, obtained from the roentgenogram with its movement under the bulb of the densitometer in the direction I -- II.

Figure 20 is a diagrammatic example of the densiographic method of studying wall thickness. In Figure 20, (b) shows a cross section of the tested object, (c) represents the recorded curve of changes in current strength in the photocell (densiogram), and (a) shows a schematic representation of the different thicknesses obtained on the roentgenogram. The darker parts of the latter indicate a smaller wall thickness (less absorption of X-rays). The extent of a depression in millimeters corresponds to the peak on the densiogram (c). The progressive rise of the curve from II to I,

i.e., the increase in darkening, corresponds to the thinning of the X-rayed sample.

Besides this method of recording and measuring the density of a negative, there are a number of other techniques, in which a form of light receptor different from the photocell is used to record the light passing through variously dense parts of the negative. Such densitometers, or self-recording photometers, have a more or less complicated design depending on the problems presented in measuring differences in negative density.

RADIOGRAPHIC TECHNIQUE

Having presented the basic principles and uses of the radiographic method, let us consider the technique involved in some examples and different stages of the work. Before the tested object or objects are placed under the tube, they must be numbered, and then divided and sorted into different radiographic groups according to the system accepted for the particular item.

Then the object must be placed under the tube in such a way as to get the best possible results. Depending on the type and location of the detail, it is sometimes necessary to place it at an angle to the central ray. The film may be placed in a cassette or wrapped in black paper. Also, the envelope with the film may be placed inside a cylindrical joint.

When the object is put in place, measures are taken to shield the cone of rays with lead or limit it with a diaphragm. Various filters, foils, intensifying screens, etc, are employed at this time.

This, and also the proposed photographing method, must be arranged beforehand. It is useful to write all the details of the work in a journal. After the exposure, the film is developed, fixed, washed and dried.

The dry negatives are examined by diffuse transmitted light of sufficient intensity to show contrast in the darkest places. The most important part of the whole process is analyzing the films and reaching conclusions. Reaching them requires sufficient experience with radiography and a knowledge of the technological process involved in the manufacture of the given item.

In examining the negative one must first identify those defects which are connected with poor quality of film or its bad handling. The light and dark picture is then examined and the reasons for different densities in different parts of the negative established. Non-uniformity of density may have the following origines:

(a) Inequalities in the thickness of the object, which are a natural and unavoidable result of its form. The light-dark picture caused by this may be analyzed by comparing the form of the object in reality with its image on the film;

(b) Non-uniformity of densities of the materials composing the radiographed volume, caused by the presence of other materials (for instance reinforced concrete containing iron reinforcement, or metallic parts joining wooden structures); this is also easily analyzed with a knowledge of the given construction system.

(c) Inequalities in the thickness of the material not antici-

pated in its construction; this is considered a defect. Examples are blisters, porosity, cracks in castings, non-fusions, cracks and pores in welded joints, etc;

(d) Non-uniformity in the composition of material produced by the presence of foreign substances, for example, slag inclusions, sand (in castings), foreign metallic inclusions frequently seen in plastics);

(e) Non-uniformity of material due to the poor mixing of some mixture, as a consequence of which there may be a lack of one substance and excess of another, differing in densities. Unequal precipitation of some component of an alloy upon its cooling, etc. (liquefaction).

The deciphering or analysis of roentgenograms has the purpose of determining the form of defects and their origin, and in the long run, of determining whether the defect can be allowed in a particular part of the item without detriment to its function. The latter is a rather difficult problem. Each plant sets up its appropriate technical tolerance standards for different items on the basis of various tests of materials and products and also the experience of the plant. It is essential to be governed by these rules. However, the rejection of items solely on the basis of picture appearances cannot be considered as a final decision. There are cases in which small defects are found in items which were not previously encountered, and are not included in the technical acceptance standards. Under these conditions it is necessary to have a joint discussion and decision by the roentgenographer, engineer or metallurgist, designer and representatives of the

technical control department and the receiving department of the client.

X-RAYING OF PRODUCTS OF DIFFERENT TYPES

Metallic products subject to X-ray testing in plants can be divided into categories depending on the technology of their production, for instance, castings, rivetings, forgings, stampings, pressed products and welded joints.

In addition, nonmetallic products of various origin may be tested. This type of grouping arises basically from the types of defects found in the listed categories of products. Depending on this, the type of radiography may vary somewhat, too, in spite of the fact that the general rules and principles given above are observed in all cases.

Cast Products

The defects in castings, disclosed by radiography, are presented in Table 4.

In mass production plants two types of testing are usually carried out: the so-called control testing (serial X-raying), in which only those parts of the object which are most subject to defects are X-rayed. With an established production technology for an item this type of testing is made selective, i.e., a certain percentage of the total plant production is radiographed. The percent for different items may vary and is established by the technical conditions of control and utilization. When a new production technique is being set up, the product is X-rayed 100 percent

at first (as in the case of the appearance of a high rejection rate for any reason in an established technology).

Besides control X-raying, there is also technological, in which all the parts of a particular item suitable for X-ray testing are radiographed. This type of radiography tests the technological production process for the item and is carried out periodically with the continuing production of one type of product.

In those plants which make use of fluoroscopy, the primary control is done by this method. In the case of defects which leave no doubt, the rejection or passing of the item takes place on the spot. In doubtful cases the item proceeds to additional testing by the photomethod, on which basis the final conclusions are reached. Also those items which are too thick to be examined fluoroscopically are sent on to the photomethod.

In order to increase prodictivity the greatest number of items possible are X-rayed at one time, which sometimes requires placing the tube 180-230 centimeters away from the film. Some increase in exposure is associated with this. In order to get the best use for the apparatus, i.e., to increase its coefficient of profitable activity, all the preparatory operations with the items are carried out in such a way that as soon as the radiography of one piece is finished, another is fully ready to be placed under the tube.

At the present time X-ray control is being used in the most diverse branches of industry.

X-ray control is widely used for the testing of lead-bronze bearings, for the discovery of cracks, precipitation of lead

(liquefaction), pores, and slag inclusions. It is essential to note that many cast objects can be repaired after a defect is found in them, as, for instance, by inserting welded plugs. After such repair the item is again X-rayed to find out how well the defect has been removed and corrected.

Figure 21. [Photo] An X-ray picture of shrinkage friability in an aluminum alloy casting.

Figure 22. [Photo] Blisters in an aluminum alloy casting.

Figure 23. [Photo] Cracks in a casting. [See Table 4 on following pages]

Forged and Stamped Products

These items are very unsuitable for control by X-raying, and the results of such tests are usually negative. Such defects as blisters, gas pores, and large cracks, are pressed-out in forging and stamping. Their thickness, expressed as a percentage, becomes so small as to be below the sensitivity limits of the method. In stamped and pressed objects it is only possible to disclose relatively large defects, which appear during these technical operations, such as large cracks, ruptures, and sometimes separation of layers, if the individual layers of metal are placed approximately in the direction of the rays. One type of forged or pressed object which is reliably checked by the X-ray method is the steel bomb for storing gas. Large cracks are fairly often detected at the base of the bomb, which are formed during the production process, while af-

TABLE 4

DEFECTS IN CAST PRODUCTS, REVEALED BY X-RAYING

Defect Group [1]	Defect Type [2]	Reasons for the Defect [3]	Indications on Roentgenogram [4]
Shrinkage	1. Shrinkage flaws 2. Porosity	1. Insufficient charging of the casting. 2. Incorrect placement or unharmonious size relationships of cooling coils. 3. Unsuitable chemical composition of metal. 4. Incorrect temperature of casting metal. 5. Slagging or clogging of the gate screens. 6. Unsuitable pouring speed. 7. Unsuitable pouring gate system.	1. Darker spots, varying in form and with unsharply defined edges. 2. Darker spots of the most varied shape, sometimes in the form of mutually intersecting lines or stripes. The edges are unsharp, sometimes with an elongate form similar to worm holes in wood, often with very marked darkening (Figure 21). Figure 21. An X-ray picture of shrinkage friability in an aluminum alloy casting.

[1]	[2]	[3]	[4]
Gas formations	3. (a) Gas blisters (b) Gas bubbles 4. Gas porosity (a) General (b) Zonal	1. Increased moisture content of mold sands. 2. Low gas permeability of molding sand and cores. 3. Presence of organic admixture in molding sands. 4. Tight packing of the mold and cores. 5. Absence or clogging of gas channels. 6. Dissolved gas in metal. 7. High pouring.temperature. 8. Too rapid pouring (splashing of metal). 9. Dampening of molds due to long delayed casting. 10. Poor design of item. 11. Fusion of inserted charges (burden).	3. (a) Darker spots, often of an elongate form, with branching. The edges are fairly sharp and extend to edge of casting. (b) Darker spots of a round form, with a diameter of 1 to 5 millimeters, usually concentrated in the upper part of the casting (Figure 22). Figure 22. Blisters in an aluminum alloy casting. 4. Smaller, darker spots with a diameter of 0.3 to 1 millimeter, or streaking, distributed with varying density, sometimes uniformly over the whole casting or in particular zones.

[1]	[2]	[3]	[4]
Cracks	5. Macro-fissures	1. Inadequate feeding of overflow gates.	5. Thin, darker, broken zig-zag lines, sometimes with branching (Figure 23). Figure 23. Cracks in a casting.
	6. Micro-fissures	2. Improper gate system.	6. A defect characteristic of magnesium alloys. The roentgenogram shows an over-all effect of separate micro-fissures in the form of friability, often arranged in layers almost parallel to each other. The picture may be reminiscent of brush marks or bird feathers.
		3. Unsuitable chemical composition of alloy.	
		4. High pouring temperature.	
		5. Bad "modification".	
		6. Premature knocking out from flask.	
		7. Unfavorable structure of item: sudden transitions, sharp corners, etc.	
		8. Increased toughness of cores (insufficient elasticity).	
Non-fusions	7. Non-fusions	1. Poorly arranged cooling coils and absence of gas channels.	7. Dark threadlike lines. Can be seen on pictures when the plane of the non-fusion is parallel to the direction of the rays or at a small angle to
		2. Low pouring temperature.	
		3. Poor core drying.	
		4. Unsuitable composition of	

[1]	[2]	[3]	[4]
		molding sand and cores.	it, analogous to the exposure of cracks.
		5. Poor ventilation of the form and core.	
		6. Improper gate system.	
		7. Incorrect assembly of form.	
Non-filling	8. Non-filling (gaps in the body of the casting.)	1. Improper gate system.	8. Dark spots of variable form. Sometimes thin dark bands.
		2. Interrupted flow of metal.	
		3. Slow pouring speed.	
		4. Low pouring temperature.	
		5. Non-uniform dampness of form and cores.	
Inclusions	9. Slag or flux inclusions	9 (a) Metal, strongly saturated with gases or oxides.	9. Darker spots and points with improper contour, with more or less sharp outlines.
		(b) Incorrect chemical composition.	
		(c) Improper cross-sections in gate system.	
		(d) Large cross-section of screen.	

[1]	[2]	[3]	[4]
	10. Dirtying	10. (a) Poor quality packing and removal of form; poor cleaning of cores. (b) Low strength and dampness of forming and core sands. (c) Careless movement of assembled form. (d) Wearing or poor upkeep of roller conveyers.	10. Darker spots of varying size and configuration. Not exposable in magnesiu alloys.
	11. Metallic	11. Incorrect arrangement of overflow gates and sprues.	11. Depending on the density of the inclusion, more or less dark spots or points with sharply delineated edges are obtained.
Precipitation of alloy components	12. Liquefaction (instead of nonuniform distribution of alloy com-	1. High pouring temperature. 2. Poor mixing before pouring. 3. Insufficient rapidity of pouring.	12. In case of the precipitation of less dense components - darker spots; in case of lique-

[1]	[2]	[3]	[4]
	ponents).	4. Presence of contaminants.	faction of more dense components - light spots. The contours of such spots may have the most varied shapes, as for example, screens, points, streaks.
Defects which arise during welding repairs	13. Slag.	13. Poor mixing of flux salts.	13. Dark spots of varying form. With the inclusion of barium chloride (with the welding of magnesium alloys), the spots are lighter on a dark background and have sharply defined edges.
	14. Non-welding	14. Insufficient fusion of welded area.	14. Dark spots of varying shape and size.
	15. Cracks	15. Insufficient heating of object during welding.	15. Dark broken lines.

ter some time in use, corrosion may be observed in parts of the bottom and walls of such vessels.

Riveted Joints

Cracks and gaps between the rivet head and wall are primary defects which are shown up rather easily by the X-ray method. Difficulties in their discovery are basically due to difficulty in approach with the tube or problems in loading the film.

Welded Joints

The technique of X-raying welded parts depends not only on the material, form and size of the object, but also on the type of welded seam itself.

Defects which are disclosed in welded joints by the X-ray method depend on the type of welding, for instance, arc, torch, atomic-hydrogen, or contact (point or roller). In comparison with the technique of X-raying cast objects, the testing of welded joints involves additional problems in exposure of defects, stemming from the very inconvenient "approach" of the tube, i.e., from the impossibility of giving the rays the proper direction. This is due to the usually complex configuration of the welded joint or knot. In some cases it is not possible to place the film in an expedient way; besides that some defects, which are characteristic of welded joints, demand a particular ray direction for their exposure.

Fusion Welding

Defects which are found in welded seams with metal fusion may be divided into three groups:

(a) inclusion of gas or slag in the fused metal;

(b) non-welds: absence of a connection between the primary and fused metal, or between the separate beads of the seam;

(c) cracks, which are found both in the regions of the primary material adjacent to the seam and in the fused metal. This defect may arise both during the welding and heat (thermal) treatment of the object.

Besides these primary defects, one may also note undercutting or thinningof the metal walls adjacent to the seam, and melting -- the passage of excess fused metal through the walls of the object.

(a) Gaseous inclusions (blisters, friability) appear on the film as darker, rounded points. Sometimes these points are joined in a chain or form a certain plane with a more or less dense distribution. Slag inclusions have a somewhat less orderly form than pores, and are sometimes distinguishable from pores on a film by their less sharp outlines. However, a certain amount of experience is required to confidently separate gas and slag inclusions on a picture. The direction of the rays does not play as important a role in the exposure of inclusions as in non-welds. Usually, if the problem is the discovery of non-welds, the ray direction is chosen with regard to the exposure of this defect. Scale, which makes analysis of the picture more difficult, must be removed from the item before X-raying. Figure 24 shows a picture of a slag inclusion in a seam.

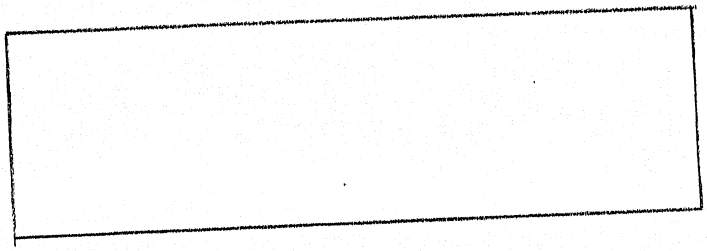

Figure 24. A Slag Inclusion in a Welded Seam of a Steel Object

(b) non-welds, i.e., the absence of a union (fusion) between the primary and fused metal, appear on photographs as darker fields, bands or lines on a lighter background, surrounding the region of the flaw. If the fusion metal is adherent to the primary one, this type of non-weld may not be shown by radiography, since the contact between the two metals is too close.

The X-raying of the left and right seams (Figure 25, 26) presents the same appearance on the photograph, i.e., the adherance cannot be detected (Figure 25). Non-welds may only be disclosed when there is a certain air gap between both metals, which may be filled with slag or oxides. [See Figure 25 on following page]

As a rule, non-welds (not of the "adherent"type) are best shown by radiography when the central rays are directed parallel to the plane of the joint, or at the least possible angle to this plane, since in this direction the thickness (depth) of the non-

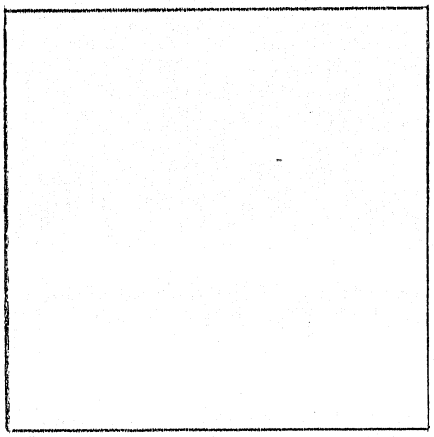

Figure 25. A photograph of an etched section of a welded "T" -joint (macrostructure). The right part shows non-welding in the form of adherence.

weld, expressed as a percentage of the whole wall thickness, will be the maximum.

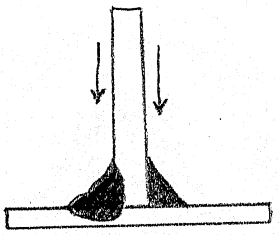

Figure 26. Diagram of the seams shown in Figure 25 Right -- adherence, left-a good weld.

Tests have [redacted] shown that in welding with thickly coated

electrodes, usually used for the welding of key parts, the X-raying should be along the camfered edges of the object. The non-weld observed in these cases along the chamfers are due to the sizeable slag layer, which is thoroughly exposed in normal radiography. In welding with electrodes having a thin coating, a thin oxide layer is formed along the chamfer in non-welds; this may be disclosed only by X-raying along the chamfer (Figure 27, 28).

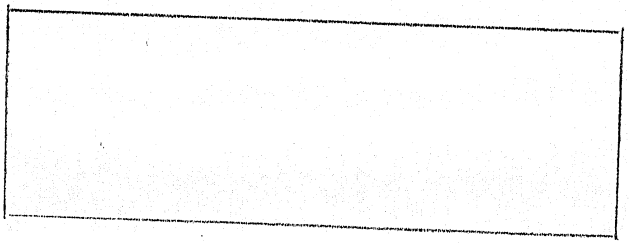

Figure 27. Roentgenogram of a V-shaped seam with non-welding along the chamfered shoulder.

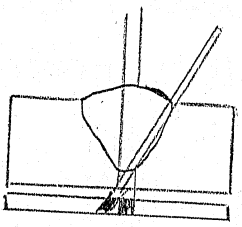

Figure 28. Diagram, showing the presence of a non-weld in the neck and along the chamfer.

Therefore, in cases where thickly coated electrodes are used, it is necessary to take X-rays normally and along the chamfers to

detect non-welds, since the image of the possible non-fusion in the neck (Figure 28) overlaps the image of the non-fusion along the chamfers when the X-rays are taken along them.

Thus the question of the X-raying direction in V and X-seams with a thickness of 6 millimeters or more is answered by thost technical requirements which are presented by the welding process.

Let us consider one more case of non-welding. Figure 29 is a schematic representation of a welded T-joint. The non-weld in

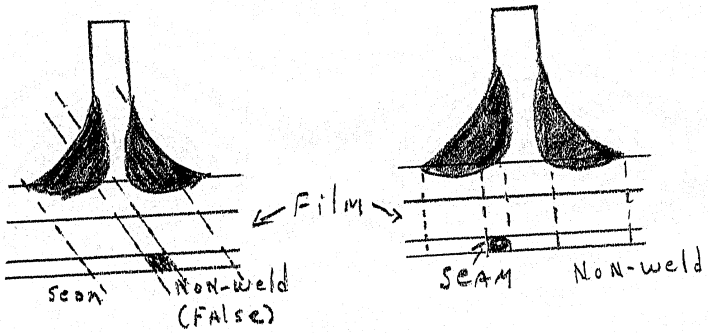

Figure 29. A schematic representation of a "bridge" non-weld: a-incorrect X-ray direction; b -- correct direction.

this case is in the corner (on Figure 29, b, on the left), between the vertical and horizontal plates a so-called bridge. Such a bridge is tolerated in some cases. In order to show it, it is essential that the rays be directed almost parallel to the vertical plate, as shown by arrow R_2. Then the image of the non-weld will appear under the corner. However, if the rays are directed as shown by the arrow R_1 in Figure 29, a, where there is no bridge non-weld, the image of the gap between the plates appears in the same place as it would

appear, with this ray direction, if there was an image of a bridge that might be present. With this ray direction it is impossible to say whether a darkening on the film is caused by a non-weld in the corner, or by a gap between the plates.

This example shows the importance that the direction of the central rays has in some cases. Therefore, in the analysis of roentgenograms of welded joints it is especially important to know the radiation direction and take it in consideration when examining the pictures.

(c) In the welding of large thickness carbon steel, cracks are formed mainly in the metal which is fused on. With special steels they may also include the primary metal. For the best exposure of cracks it is especially important to place the film as close as possible to the seam and avoid scattered radiation. The thickness of cracks also plays an important role in their disclosure. In the radiography of welded connections, special attention must be given to the presence of possible, and in many cases unavoidable, gaps which are encountered in certain types of joints.

The image of such a gap on the picture may overlap the image of a possible non-weld at this point or in the immediate vicinity. This example is shown in Figure 29. Another case is given in Figure 30. Two trough-shaped halves are butt-welded together. [See Figure 30 on following page] If for technical reasons the weld must extend the full thickness of the wall, as is shown in Figure 30, a, with a good execution of the weld no dark places or lines along the seam will be visible on the film. If, however, the seam is made as in Figure 30, b, i.e., it is not welded along

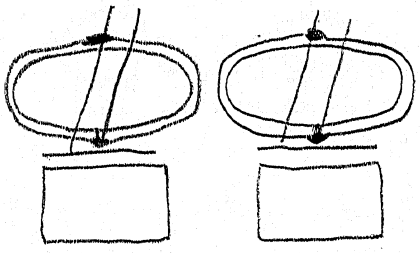

Figure 30. Schematic diagrams of different pictures on the photograph with the X-raying of butt welds with a welding (a) and a weld which does not extend the full thickness of the wall (b)

the full thickness, the image of these areas will show dark lines because of the decreased thickness of metal.

When a full weld is required, but dark lines or areas are present, one may conclude that the weld is unsatisfactory.

Contact Welding

Unlike the types of welded seams considered above, contact welding does not make use of fused-on metal to join the welded parts. In this case the welded plates or sheets are placed between two electrodes, which are heated by passing a strong current through them. The metal found between the electrodes is heated and forms a so-called spot weld with a fused central part -- nucleus, which is also the main connection (joint)between the welded sheets.

In spot-welds which have the usual diameter of several millimeters, radiography will easily disclose cracks (often directed along radii, in the form of rays from an area close to the center of the spot)(Figure 31,a),and

also pores, blisters (Figure 31 b) and spattering of the metal from the point in the plane of the touching sheets.

However, it is not so easy to show non-welds in this case. In the seams considered earlier, non-welds were evident from an absence of fused metal between the welded surfaces, or the presence of slag on air strata, which gave more or less distinct dark regions on the picture. The absence of a weld in spot welds is due to an insufficient depth of fusion and the formation of a spot nucleus which is too small. No stratifications or hollows are formed here. Thus a non-weld with spot welding can only be discovered by radiography in cases where the nucleus size (its diameter and thickness) can be determined by this method.

There are indications in literature that in the spot-welding of certain alloys of the duraluminum type it is possible to draft the spot nucleus by radiography, and to judge whether it falls within the required limits, i.e., if there is sufficient welding, by its diameter. However, the results obtained do not allow evaluation of the reliability of the method, so that it could be recommended for a serial testing of non-welded spots in plants. The results obtained with the testing of steel items are negative.

Non-Metallic Products

A series of products is produced from non-metallic materials by the machine-building industry, as for instance rubber tires for automobiles and air craft, various gears and other small items from plastic for various steering and automatic systems, wooden parts of a particular size for certain aircraft, etc. All these materials may be tested by radiography. The discovery of defects, specific for each

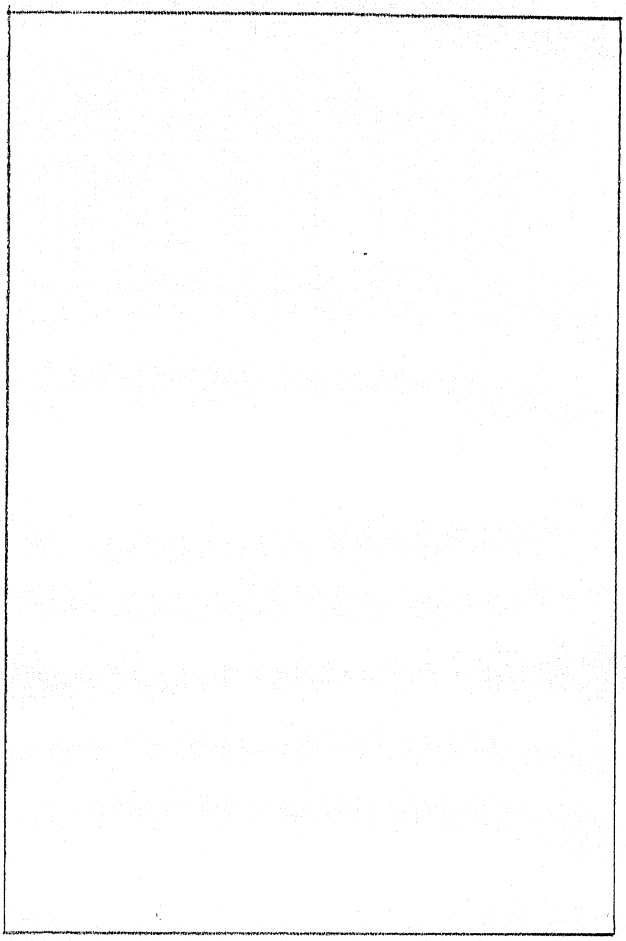

Figure 31. Roentgenogram of a spot weld (magnification ca. x 10): a - cracks; b - blisters.

material, is based on the different densities of the unwanted inclusion and the primary mass, which produce a corresponding contrast on pictures. For instance, pitch has a greater density than wood, and therefore gives a light image. Glue, binding two layers of veneer, is also less transparent for X-rays than the wood itself. The grain of the wood and its direction, as well as cracks in the material, can be distinguished on pictures.

More dense metallic inclusions are often discovered in plastics. With suitable methods, pictures of thin layers (micro-roentgenography) can show the fibrous or granular structure of the material.

CONVEYER X-RAYING

In X-raying, a considerable portion of time is spent in preparatory and supplementary operations to exposure. This time consumption is notably decreased if the next item is placed under the tube immediately after the removal of the X-rayed one. This is accomplished in conveyer X-raying. In this method, the previously prepared item is installed on a transport belt and conveyed automatically, after the necessary length of time, under the tube, where it is held for the necessary interval and then removed. The cassette or envelope with the film is passed on to a specially equipped darkroom, where it is developed on automatic conveyers.

The conveyer method of radiography necessarily gives high production, but it is not completely suitable for all items. It is feasable for comparatively small objects with a simple design, which do not require X-raying in several positions (repeats).

With large, intricate items which require separate X-raying

of their various parts, under various working conditions, different placing of the film, etc, such conveyer feeding is not possible. However, when possible it is worthwhile to mechanize separate phases of the X-raying, for example, the preparation of theobject or its placement under the tube. Such mechanization is practical in the radiography of welded boiler seams, in which case the item is brought to the tube on a special platform and is rotated automatically on its axis as a function of the exposure or (for the X-raying of extended seams) moved in front of the tube along its axis.

The partial mechanization of product conveyance, movement of the item during testing on a screen, etc, has been instituted in a number of plants, depending on the local conditions. For example, one item is prepared and installed on one half of a rotating table while another one, previously placed on the second half of the same table, is X-rayed in an enclosure. The X-raying of aircraft ribs (longerons) is practical and the facilities for it have been mechanized.

A series of small accessory fixtures and attachments making the testing of such items as valves and bearings easier and faster, have been included in the control practices of various plants.

In order to test very large objects, which cannot be brought to the laboratory, and also various assembled machines, it is essential to use portable X-ray equipment. In ship-building, the railroad industry, in aircraft hangars, etc, the X-ray apparatus is mounted on trucks, cranes, in wagons, or automobiles and carried to the object to be tested. The X-ray tube, connected to the high-voltage generator by the use of special cables, is removed from the portable station and secured on a special rack, stand, etc, near the X-rayed object, at the proper distance and with the required X-ray direction. The photographic

processing of the films and analysis of the pictures is also done here in a specially equipped darkroom, which is one of the components of the movable station.

PROTECTION IN WORK WITH X-RAYS

Working with X-rays is included in the category of hazardous occupations, and for this reason it is essential to follow certain rules for personnel protection and safety, bearing in mind that:

(1) X-rays, absorbed in the human body, may produce various changes in it depending on the quality (wavelength), intensity and duration of exposure. As a result of the action of X-rays on the organism, there may follow burns of various degrees, changes in the blood, falling of hair;

(2) In working with high voltages, especially in stationary installations without high-voltage cables, ozone and then gaseous oxides of nitrogen are formed. The latter have a harmful action, producing fatigue and headaches;

(3) Finally, high-voltages, which are not harmful to the health in themselves, require the maintenance of certain rules guaranteeing electrical safety, in the sense of avoiding accidents due to current injury or shock.

With the observance of suitable rules and regulations the listed forms of danger are eliminated. Protection from the direct action of X-rays is accomplished by: (1) protective shields, which prevent the worker from getting more than the allowable dose per second, and (2) giving the workers in X-ray laboratories decreased working days and additional leave, since a repeated or extended exposure to harmless second doses may cause an accumulation of radiation in the organism in an amount equal to the sum of the doses.

The protective materials used for walls, partitions and doors may be substances which strongly absorb X-rays (lead, baryto-concrete), or materials which are poorer absorbers, but of much greater thickness (concrete, brick, etc). The existing protection standards are usually given in the necessary thickness of lead in millimeters at a particular voltage. The higher the voltage, the greater must be the lead thickness. If the lead is replaced by another material, its thickness should be as fully protective as the lead. The lower the density (specific gravity) of the material which replaces lead, the thicker it must be. Equivalent thickness tables for such materials as baryto-concrete, concrete, brick, iron and copper are available.

When X-ray laboratories are equipped, such protection must be foreseen and guaranteed. It is planned and carried out in accordance with the type of apparatus, layout of the space, its dimensions, the character of the walls and partitions, specifications of the neighboring laboratories, etc.

Avoidance of the harmful effects of gases formed in the work with X-ray apparatus is accomplished by good ventilation, for which there are also certain standards regarding magnitude.

As far as electrical safety is concerned, it is built into the latest type of X-ray equipment (with cables) produced. Furthermore, the usual rules for working with high voltages must be followed, as presented in OST-5067.

CONCLUSION

This short survey has shown the technique and advantages of using X-rays for improving the quality of materials and products, and for increasing the fruitfulness of their use. They allow the examina-

tion of internal structure of a substance and location of the flaws it may contain. From the time of the first use of the radiographic method, i.e., over the course of 50 years, this method has been greatly improved. While at first it was used exclusively in medicine for the examination of the human body, comparatively transparent to X-rays, in proportion to the development of X-ray apparatus design, perfection of methods, and improvement in the quality of photo materials, it has become possible to X-ray thickness as great as 300 millimeters of steel, using an apparatus of 2 million volts, which makes use of the principle of transforming low voltages into high. Other principles of obtaining highly penetrating X-rays have also been put into use, for example, the technique of accelerating free electrons in a circle with an electromagnetic field in electromagnetic accelerators. This type of installation allows the production of X-rays with a "hardness" of 20, 100, and 250 million volts. The thickness of metal which may be examined increases correspondingly.

Over the course of several decades, Russian scientists have added quite a few new ideas to the field of testing materials and applying X-rays for the solution of a number of practical problems. There are numerous articles, reviews, and books on a number of questions of X-rays application, through which the reader may become more intimately acquainted with both various individual problems than can be solved with the aid of X-rays, and the methods which can be used to get answers to the problems that are presented. Here too we cannot fail to mention certain workers, who were among the first to apply their labors, for us in the USSR, to the application and development of the X-ray method in plants. These pioneers were N. Ya. Selyakov, G.S. Zhdanov, N.K. Kozhina, and S.T. Nazarov and their assistants, who practiced X-ray checking in the early stages of its development in plants with a fairly wide

diversity of products. At the present time, almost every plant which uses this type of checking has personnel which are perfecting various phases of the control process by the introduction of special devices which make it easier and better, thereby leading to further progress in machine building.

TABLE OF CONTENTS

-E N D-